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TECHNOLOGIES FOR ENERGY FROM BIOMASS BY DIRECT COMBUSTION, GASI--ETC(U)
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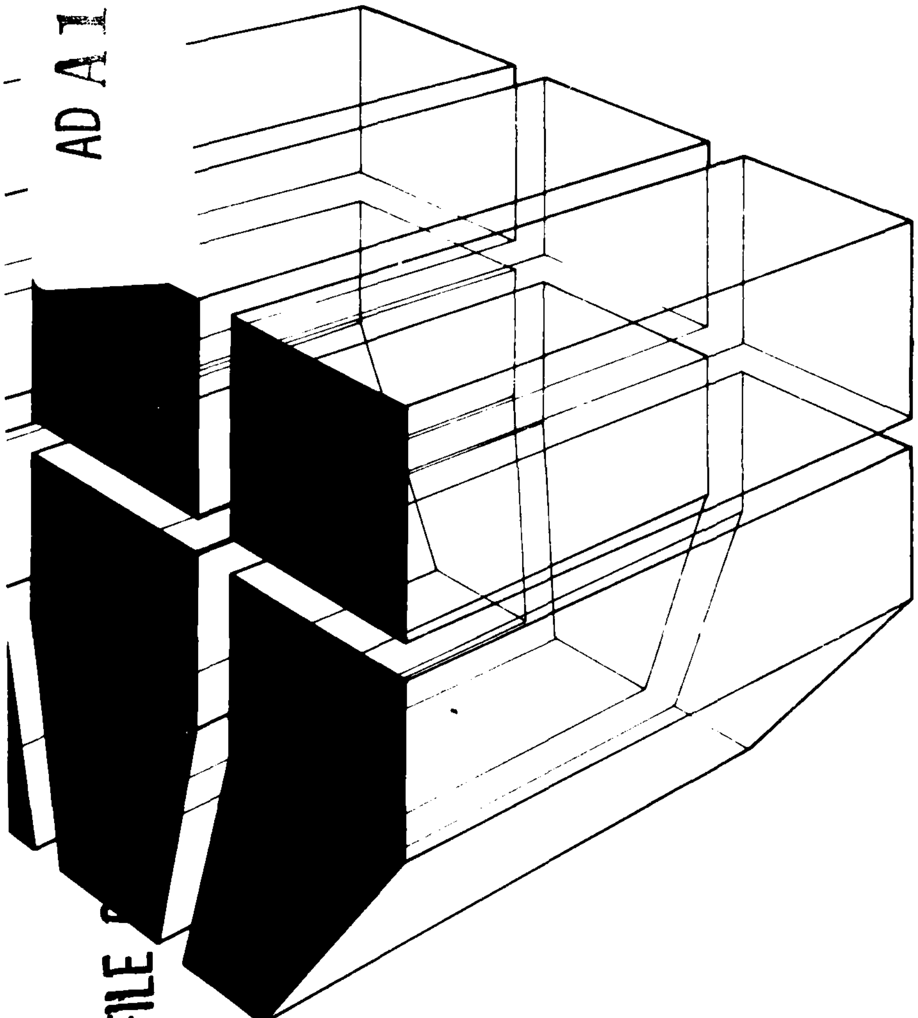
TECHNICAL REPORT E-172
May 1981

TECHNOLOGIES FOR ENERGY FROM BIOMASS BY DIRECT COMBUSTION, GASIFICATION, AND LIQUEFACTION



by
A. Collishaw

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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER CERL-TR-E-172	2. GOVT ACCESSION NO. AD-A100323	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) TECHNOLOGIES FOR ENERGY FROM BIOMASS BY DIRECT COMBUSTION, GASIFICATION, AND LIQUEFACTION		5. TYPE OF REPORT & PERIOD COVERED FINAL 6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) A. Collishaw		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS U.S. ARMY CONSTRUCTION ENGINEERING RESEARCH LABORATORY P.O. BOX 4005, Champaign, IL 61820		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 4A762731AT41-G-007
11. CONTROLLING OFFICE NAME AND ADDRESS		12. REPORT DATE May 1981 13. NUMBER OF PAGES 95
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

Copies are obtainable from the National Technical Information Service
Springfield, VA 22151

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

wood
biomass conversion
fuels

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This study appraises the technologies available to produce energy from biomass (wood). Direct combustion, gasification, and liquefaction methods are discussed as they relate to Army-scale (3 to 250 million MBtu/hr [.88 to 73 MW]) central heating plants.

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The study found:

1. There is little economic data for energy-from-wood technologies; however, ranges of anticipated costs are given.

2. Combustion-based wood fuel technology is well established in this country. Of the five types reported, spreader-stoker and fluidized bed combustors are the most advanced.

3. While not as advanced as combustion-based wood fuel technology, wood gasification/liquefaction technologies are expected to emerge as demonstrated technologies in the near term.

It is recommended that Army planners consider, and if the economics are favorable, submit wood-fueled, combustion-based heating plants as part of the normal Military Construction program for 1983 through 1988.

FOREWORD

This research was performed by the U.S. Army Construction Engineering Research Laboratory (CERL) for the Directorate of Military Programs, Office of the Chief of Engineers (OCE), under Program Element 6.27.31A, "Research and Investigation Program"; Project 4A762731AT41, "Military Facilities Engineering Technology"; Task G, "Military Energy Technology"; Work Unit 007, "Waste-Derived Fuel (WDF)." The OCE Technical Monitor was Mr. B. Wasserman, DAEN-MPO-U. Mr. A. Collishaw of the CERL Energy Systems Division was the Principal Investigator.

Appendix A was prepared by Clark, Dietz Engineers, Inc., Urbana, IL, under Contract No. DACA 88-79-M-0111. Appendix B was done by SCS Engineers, Inc., Long Beach, CA, under Contract No. DACA 88-79-M-0110. SCS personnel directly involved in the study were Mr. John P. Woodyard, Project Manager, and Mr. Robert L. Yust, Project Engineer.

Mr. R. G. Donaghy is Chief of the Energy Systems Division. COL Louis J. Circeo is Commander and Director of CERL, and Dr. L. R. Shaffer is Technical Director.

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1 INTRODUCTION

Background

Two of the goals in the Army Energy Plan[1] relate to Army facilities: (1) reduce energy consumption in facilities operations by 40 percent by the year 2000, and (2) reduce the use of petroleum fuels in facilities operations by the year 2000. One possible approach to these goals is the replacement of natural gas and petroleum fuels with biomass materials. Since logging operations are common on Army as well as other Federal lands, wood (or biomass) waste appears to be a potential replacement for some of the oil and gas presently being used. Wood also has the advantage of being a renewable source. However, before a wood can be used to significantly reduce gas or petroleum usage, it is necessary to review the state of the technology for conversion of wood to energy.

Objective

The objective of this study is (1) to determine the state of commercialization of technologies for obtaining energy from biomass by direct combustion, gasification, and liquefaction, and (2) to define capital investment requirements and annual operating costs of these technologies.

Approach

The work was accomplished in three parts:

1. Articles, reports, and studies were reviewed to determine the reported state of direct combustion, gasification, and liquefaction technologies.

2. Equipment manufacturers were contacted to obtain capital cost information.

3. Biomass energy users were contacted to obtain information on operating costs and savings compared to previous fuel.

The work was accomplished primarily by contract.

[1] Army Energy Plan (Department of the Army, February 1978).

Scope

The scope of this report is limited to evaluation of direct combustion, gasification, and liquefaction technologies using biomass (wood) as an energy source. The output capacity range of interest is Army installation scale, which is from 3 to 250 MBtu/hr (.88 to 73 MW). Biomass harvesting, its management, and its equipment are not within the scope of the report.

2 FORMS OF WOOD FUELS AND COMBUSTION-BASED TECHNOLOGIES

Forms of Wood Considered for Direct Combustion

Wood, the primary biomass fuel considered for direct combustion, is available in many forms. Wood is low in sulfur (typically 0.6 percent) and does not produce dangerous levels of sulfur oxides when burned, as do many fossil fuels. Since the flame temperature in a wood fire is lower than in a coal, oil, or gas fire, the level of nitrous oxides produced is lower. The amount of particulates produced by burning wood is somewhat less than that produced by burning coal, but is greater than that from fuel oil or natural gas. Because of this, some form of particulate emissions control is required; however, relatively inexpensive mechanical collectors, such as multi-cyclones, are usually sufficient. Waste wood from lumbering operations is usually "green," with a moisture content of 20 to 50 percent. The green waste wood could be a significant energy source to the Army, because for every 1000 tons (907 mt) of wood harvested, approximately 200 to 300 tons (180 to 270 mt) remain as waste that could be chipped or hogged for use as fuel.

Pelletized wood is commercially available in some areas. This is a waste wood that has been reduced in size, dried to 10 to 15 percent moisture content, and then compressed (densified) by a pelleting operation. Pellets have better flow properties than green wood and a significantly higher heating value of approximately 8500 Btu/lb (19.8 mJ/kg), as delivered.

Sawdust, sanderdust, and planer shavings may also be available to an installation as a potential biomass fuel.

Combustion-Based Biomass Fuel Technologies

Characteristics of the following types of combustors are summarized here and discussed in greater detail in Appendix A:

	Nominal Maximum Capacity
Dutch Oven	-----
Conifer	8 MBtu/hr (2.34 MW)
Spreader-Stoker	600 MBtu/hr (176 MW)
Fluidized Bed	40 MBtu/hr (11.7 MW)
Cyclonic Combustor	50 MBtu/hr (14.7 MW)

Dutch Oven

Dutch ovens use a form of burning known as pile burning. The wood fuel is fed from above and allowed to pile up on a stationary grate. Under-fire air is supplied to partially combust, or carbonize, the fuel, thus driving off hot combustible gases. Over-fire air is mixed with these gases as they are fed into the boiler section, where combustion is completed, producing steam in the boiler tubes. This type of boiler was used extensively before 1950 but now is considered outdated because of its inefficient combustion and difficult control. Although some dutch ovens are still in operation, they are generally being replaced by more advanced furnaces.

Conifer

The conifer, Figure 1, is an updated version of the dutch oven. Rather than the wood fuel being piled onto a flat grate, however, it is allowed to flow down a series of stepped grates through which the primary air is fed. This allows for more efficient gasification and finer control since the fuel is spread in a thin layer. The hot gases are mixed with air, fed to the boiler section, and combusted.

One manufacturer of this type of boiler claims that their unit will successfully burn wet or dry hogged wood, planer shavings, sawdust, sanderdust, wooden pellets, and bark. The same company also offers retrofit units which convert fuel oil and natural gas-fired boilers to wood-fired units. One limitation which the retrofit system has is size. The literature indicated stock units were available from 0.75 MBtu/hr (.22 MW) to 8.40 MBtu/hr (2.5 MW) heat capacity.

Spreader-Stoker

The spreader-stoker, Figure 2, is the most commonly used system for burning wood fuels. In this type of boiler, the fuel is thrown onto a grate by a mechanical or pneumatic spreader. The grate can be stationary or it can be equipped for ash removal by traveling, oscillating, or dumping. Under-fire air is fed in through the grate and over-fire air is supplied above it. Much of the combustion actually occurs in suspension above the grate as the fuel contacts the hot gases. Larger pieces fall onto the grate where combustion is completed.

Fuels best suited for spreader-stokers are hogged fuels and pellets. Maximum allowable moisture content is 50 percent. Another possibility is the firing of spreader-stokers using a mixture of wood fuel and coal. The wood aids in boiler operation as well. Decreased slagging of firewalls, decreased ash bed clinkering, decreased ash production, and improved superheat temperature stability are all observed.

Factory assembled packaged spreader-stoker boilers are available in up to 75 MBtu/hr (22 MW) capacity and field-erected units can produce as much as 600 MBtu/hr (176 MW). Coal-fired spreader-stoker systems can be fired on wood fuel with little modification.

Retrofitting this type of system is practical. Extensive furnace modification is required and substantial derating of the boiler results. If retrofit of an oil or gas boiler is desired, other types of wood furnaces -- such as conifers or fluidized bed combustors -- would be a better choice.

Fluidized Bed

A relatively new advancement in wood-burning technology is fluidized bed combustion, as illustrated in Figure 3. In this process, the combustion and heat exchange functions are separated. The combustion takes place in an inert bed of sand or small pebbles which is fluidized (suspended) by air forced from below. Fuel is fed from above and is preheated and partially combusted by the hot combustion gases before falling into the bed where combustion is completed. Impurities such as ash and contaminants are continuously removed by

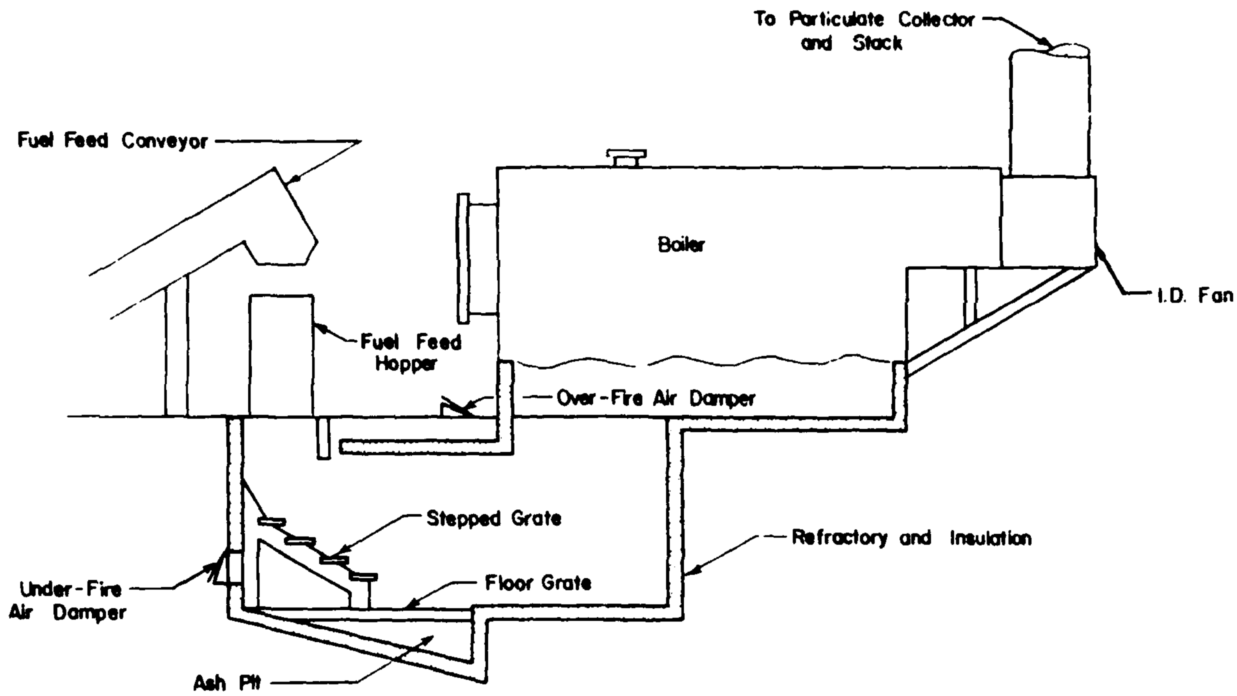

Figure 1. Conifer furnace.

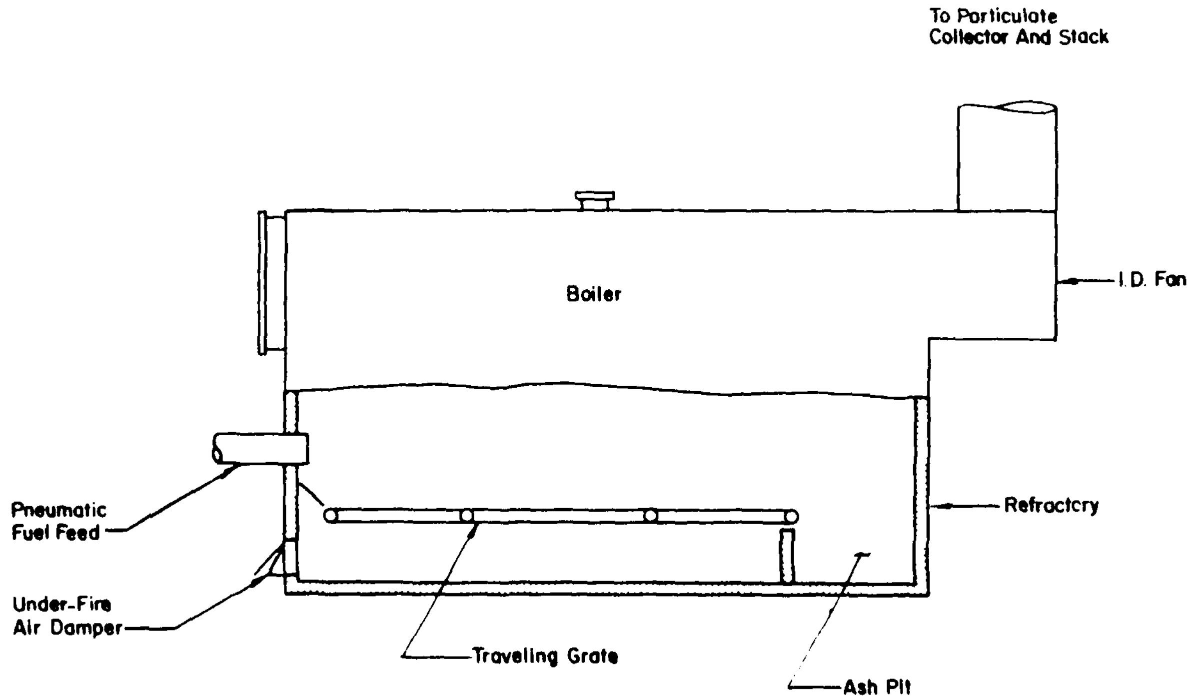

Figure 2. Spreader-stoker furnace.

screening a bleed stream of the bed media, after which the media is returned to the bed. The hot combustion gases are piped to an adjacent heat recovery boiler for steam production. Startup of a fluidized bed combustor is achieved using an auxiliary fossil fuel such as oil or natural gas to pre-heat the bed.

Until recently, these combustors were available only in packaged units no larger than 40 MBtu/hr (11.7 MW) heat output. Further developments, however, have made practical the production of field-erected units as large as 160 MBtu/hr (46.9 MW).

Since the furnace and boiler are separate units, this type of system lends itself well to retrofit applications when converting from fuel oil or natural gas. The fluidized bed combustor can be mounted some distance from the boiler and connected to it with insulated ducting. The existing oil or gas burners can be left intact as a backup in the event of delayed wood fuel shipments.

A major advantage of the fluidized bed combustor is the variability in fuels it will accept. Virtually any wood fuel from sawdust to 2-in. (50-mm) diameter hogged fuel and from 10 percent to 60 percent moisture content can be burned.

Disadvantages of fluidized bed furnaces are their high electrical energy consumption and limited size. A typical power requirement for suspension of the bed is 50 hp (37 kW) for a 12 MBtu/hr (3.5 MW) furnace.

Cyclonic Combustor

A cyclonic combustor, also known as a forced vortex combustor (Figure 4), represents another relatively new advancement in wood burning technology. This type of burner was developed for a specific purpose: combustion of waste sawdust and sanderdust. For this reason, it is more limited in application than other wood furnaces, taking only dry (15 percent maximum moisture content), pulverized (1/8-in. [3-mm] or smaller) fuel.

In this type of combustor, the fuel is pneumatically fed in at one end of a refractory-lined cylinder. Combustion air is forced into the cylinder tangentially through many ports of the refractory, creating a violent swirling action. The fuel is burned while in suspension, forming hot gases that are fed out the far end of the burner to a heat recovery boiler for steam production.

The cyclonic combustor is an efficient heat producer and can be retrofitted into some existing boilers. The cyclonic combustor also has higher electrical power demands than do more conventional wood burners. The greatest disadvantage to cyclonic combustors is, of course, the limited forms of fuel it will accept.

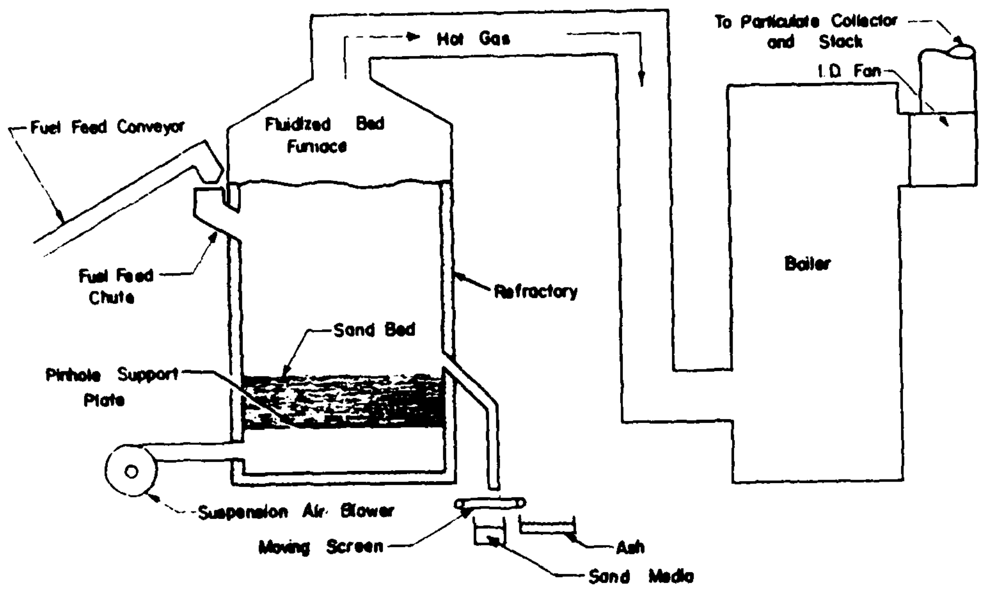

Figure 3. Fluidized bed furnace.

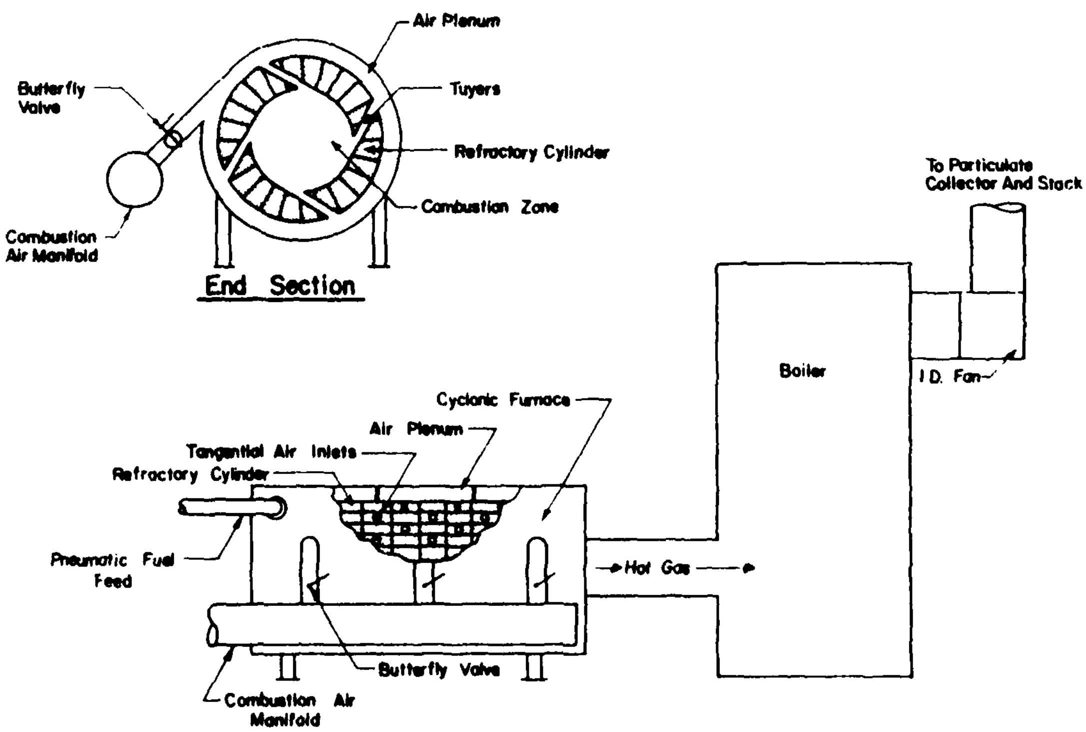

Figure 4. Cyclonic furnace.

Cost of Combustion Units

The costs in Table 1 are estimated based on 70 MBtu/hr (20 MW) output capacity and 80 percent average output for 8400 hours/year in 1979 dollars. See Appendix A for additional details.

Table 1

Costs for Wood-Burning Boilers ($K)

	Dutch Oven	Conifer	Spreader-Stoker	Fluidized Bed	Cyclonic Combustor
Capital Cost	950	1,000	1,300	1,400	1,150
PV[1] Annual Costs	19,100	16,900	16,900	15,600	15,300
Total PV Costs[2]	20,050	17,900	18,200	17,000	16,450

NOTES:

1. PV is the estimated Present Value based on 25-year economic life of boilers with a 10 percent interest rate.
2. Total PV costs is the estimated life cycle cost of the boilers.

3 TECHNOLOGIES FOR PRODUCING GASEOUS AND LIQUID FUEL FROM BIOMASS

The availability of biomass gasifiers and liquifiers is summarized here and discussed in greater detail in Appendix B. The present and near-term commercial potential of each system is emphasized. Table 2 summarizes the development status of commercial biomass conversion systems.

In this study, a unit is considered commercially proven if it has been operated successfully on a continual basis at a site other than the manufacturer's development center. A commercial development/demonstration unit is one on which preliminary testing or research is being carried out. Pilot-scale gasifiers are those units that fall below a development-scale unit, both in size and, more importantly, in degree of commercial readiness. Pilot-scale units are developed primarily to test different design parameters before a full-scale unit is built. The designation of units as commercially proven, demonstration scale, or pilot is not absolute. Instead, it serves only to compare successes of different manufacturers.

Tables 3 and 4 display information on gasification and pyrolysis systems applicable to biomass. Figure 5 shows the basic reactor designs of a wood gasifier. Each manufacturer will modify the basic design to meet the particular user's requirements. Figure 6 presents a typical process flow diagram for a wood gasification system. Specific equipment varies with the manufacturer.

Detailed capital cost estimates were not available from commercial sources of gasification systems. The manufacturers stated that the costs were very site- and fuel-specific, and that the level of controls desired was a significant variable. The following nominal gasification system costs are given for general information only:

Capacity (MBtu/hr)	Capital Cost ($)
20-30 (5.9-8.8 MW)	250,000 - 600,000
30-50 (8.8-15 MW)	500,000 - 1,000,000

Operating costs can also be estimated. The normal wood gasifier conversion process is nearly 100 percent self-sustaining. The only auxiliary fuel required is for startup. Minimal electric power is needed to operate blowers, controls, and feed mechanisms. A lumber kiln in Georgia, for example, operates a 12-MBtu/hr (3.5-MW) gasifier at a cost of only $200/month for electric power. Fluidized-bed reactors consume greater quantities of electricity for bed fluidization.

The labor required for gasifier operation is low. No more than one trained worker is required to operate an automated gasifier system, while personnel requirements for boiler and fuel-handling activities are similar to those at a coal-fired steam plant. In most cases, the gasifier systems are automated (self-regulating) and provided with alarms.

Feedstock cost and availability determine the economic viability of gasification in a particular geographic area. A delivered price of $20 or $30/ton ($18 or $27/mt) of feed material is considered to be the present upper limit to cost-effective commercial operation. The exact limit will vary from

Table 2

Expected Date of Commercial Availability

Gasification

System/Manufacturer	1979	1980	1982	1984	Not Considering Commercial Development
Alberta Industrial Dev.	X				
American Fyr. Feeder	X				
Andco, Inc.	X				
Applied Engineering Co., Inc.		X			
Biomass Corp.	X				
Bio-Solar		X			
Combustion Power			X		
Davy Powergas	X				
Dekalb Agresearch, Inc.					X
Duvant Moteurs	X				
Eco-Research	X				
Energy Products of Idaho			X		
Forest Fuels	X				
Foster Wheeler		X			
Halcyon	X				
Jamex		X			
Lamb-Cargate (Up-Draft)	X				
Lamb-Cargate (Fluid bed)		X			
Nichols Engineering & Research Corp.	X				
Vermont Wood Energy		X			
Westwood Polygas			X		
Wheelabrator Frye			X		
Wilputte Corp.					X
Wright-Malta		X			
Pyrolysis					
Alternative Energy Co.		X			
Energy Resources Co.	X				
Energy Recovery Research Group		X			
Environmental Energy Engineering		X			
Kelley Co.	X				
Tech Consultants				X	
Union Carbide				X	

Energy Content of Products

LBG = <250 Btu/scf (9.315×10^6 J/m^3)
MBG = 250-500 Btu/scf ($9.315 \times 10^6 - 18.630 \times 10^6$ J/m^3)
Char = ~12,000 Btu/lb (27.912×10^6 J/kg)
Oil = ~100,000 Btu/gal (2.787×10^{10} J/m^3)

Table 3

Overview of Commercial Biomass Gasification Systems

	Stage of Commercialization			Feed Fuel					Products			System Output Capacity	
Manufacturer	Proven	Demon.	Pilot	Wood	MSW	Corn Cobs	Coal	Densified Wood Fuel	LBG	MBG	Char	(MBtuh)	(MW)
Alberta Industrial Dev.	X			X					X			50	(15)
American Fyr. Feeder	X			X		X			X			0.25-60	(0.07-18)
Andco, Inc.	X				X				X			24	(7)
Applied Engineering			X	X		X		X	X			8	(2)
Biomass Corp.		X		X					X			20	(6)
Davy Powergas	X			X			X		X				
Dekalb Agresearch	X					X			X			10	(3)
Duvant Moteurs	X			X					X			1-6.4	(0.3-1.9)
Eco-Research			X	X	X				X			16	(5)
Forest Fuels		X		X					X			1-30	(0.3-8.8)
Halycon		X		X					X			0.25	(0.07)
Jamex		X		X		X			X			0.5-1.5	(0.14-0.44)
Lamb-Cargate	X			X					X			25	(7.3)
Lamb-Cargate		X		X					X			4	(1.2)
Nichols	X			X					X		X	80-90	(23.4-26.4)
Westwood Polygas		X		X					X			20	(5.9)
Wilputte Corp.	X						X		X			50	(14.7)
Wright-Malta			X	X						X		3	(0.9)

Table 4

Overview of Commercial Biomass Pyrolysis Systems

	Stage of Commercialization			Feed Fuel		Products				Design Capacity Input	
	Proven	Demon.	Pilot	Wood	MSW	LBG	MBG	Char	Oil	(ton/day)	(mt/day)
Alternative Energy Co.			X	X		X				25	22.7
Energy Resources Co., Inc.		X		X		X		X	X	20-150	18.1-13
Energy Recovery Research Group			X							20	18.1
Environmental Energy Engineering, Inc.*		X		X	X		X			50	45.4
Kelley Co.	X			X		X				28	25.4
Tech Consultants		X		X	X	X		X	X	50	45.4
Union Carbide		X		X	X		X			200	181.4
Wheelabrator Frye*		X		X	X		X			50	45.4

*Both companies indicated possession of technology; questions exist as to marketing control.

KEY:

Energy Content of Products

LBG = <250 Btu/scf (9.315×10^6 J/m^3)
MBG = 250-500 Btu/scf (9.315×10^6 - 18.630×10^6 J/m^3)
Char = ~12,000 Btu/lb (27.912×10^6 J/kg)
Oil = ~100,000 Btu/gal (2.787×10^{10} J/m^3)

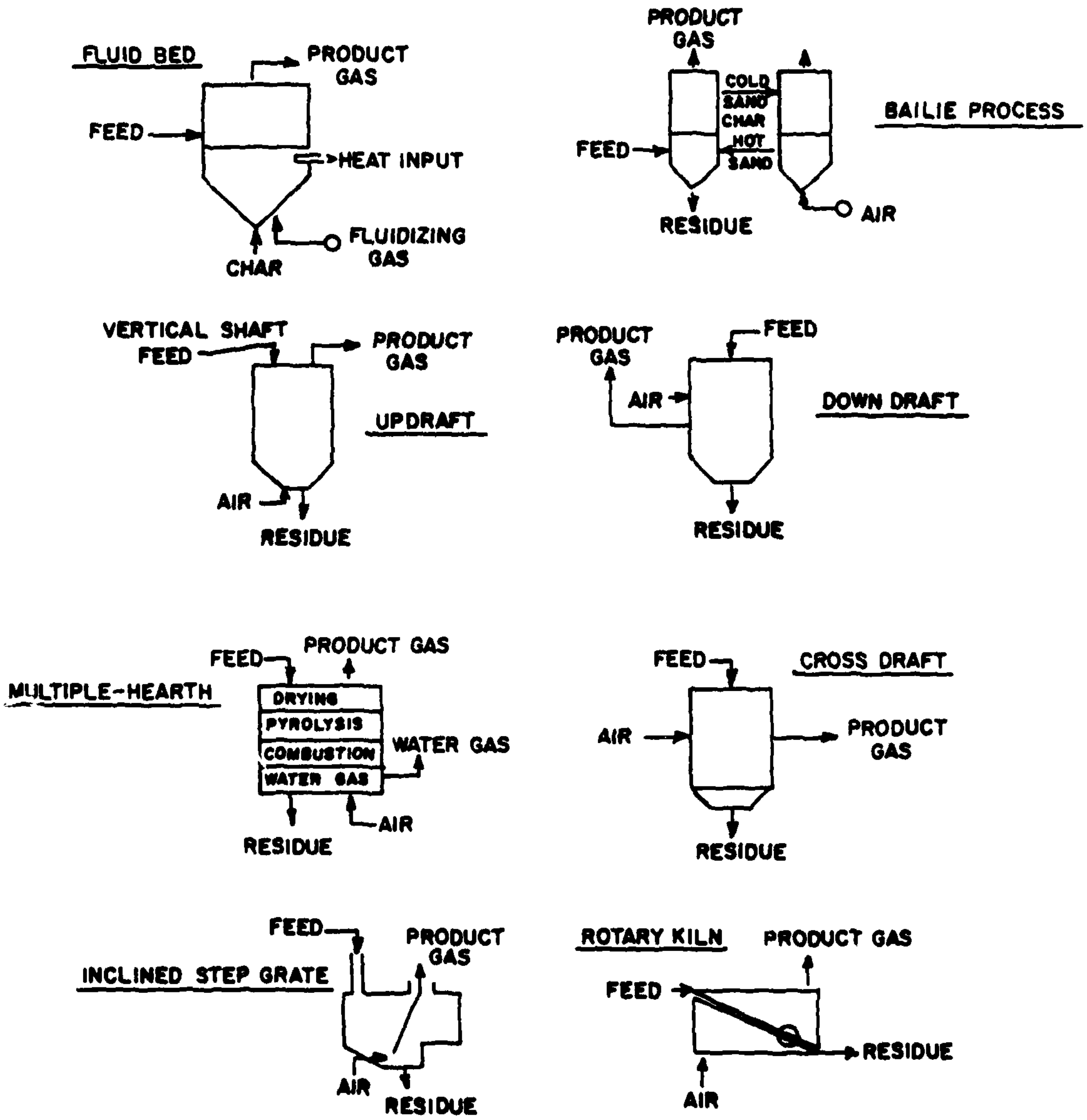

Figure 5. Basic configurations of available biomass gasification reactors.

area to area, and can be expected to increase as the price of competing fuels increases.

Maintenance requirements are low, and the repair history of most operating gasifiers is very good.

An overall technical and economic ranking of the different systems would be premature at this time as data are not available. As shown in Appendix B, 13 manufacturers actively marketed commercial installation-scale gasifiers in 1979. As more commercial-scale systems come on-line, more data will be available.

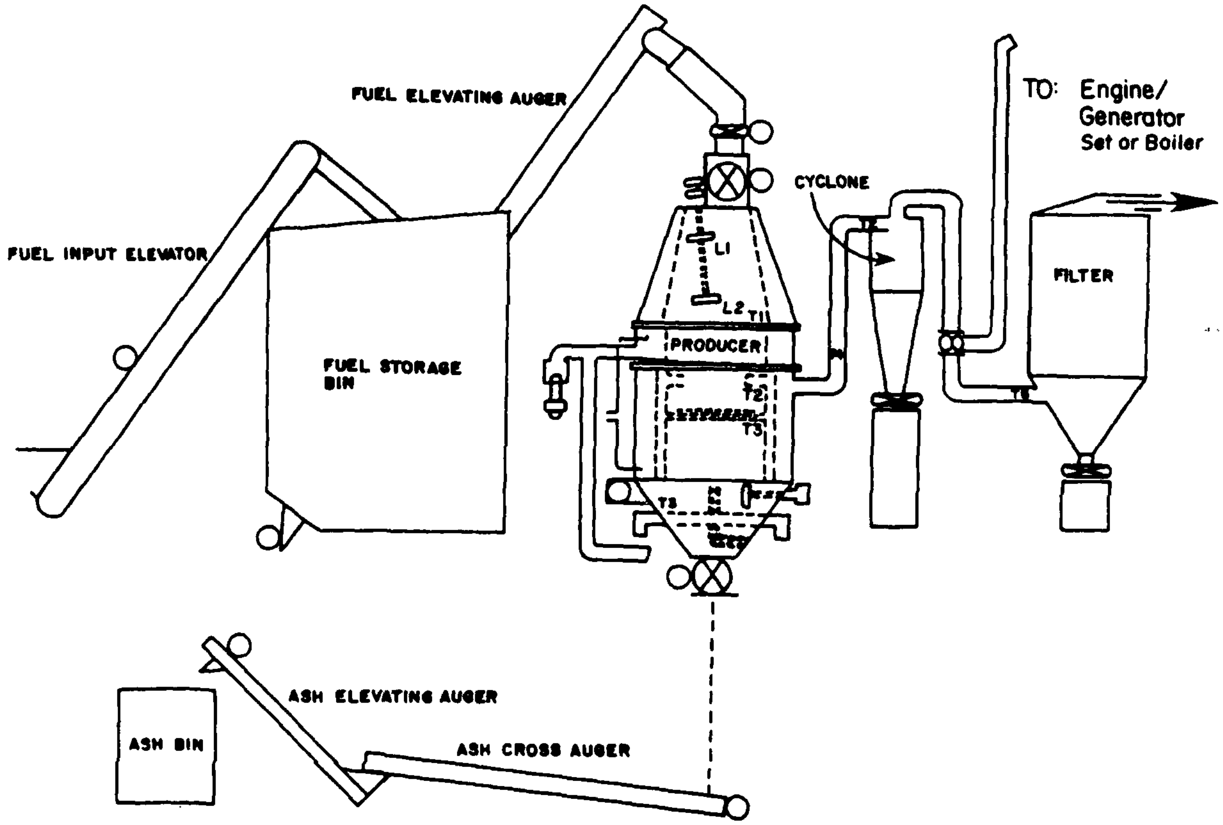

Figure 6. Example process flow for biomass gasification system. (From R. C. Lang, Feasibility Study: Commercial Biomass Gasifier at State Central Heating and Cooling Plant [California State Energy Commission, April 1978]).

4 CONCLUSIONS AND RECOMMENDATIONS

Conclusions

The study showed that combustion-based wood fuel technology is well enough established that Army planners could develop MCA projects for the period 1983 through 1988, assuming that sufficient wood fuel is available and competitively priced (Appendix A).

Five types of combustion systems are commercially available, each with at least 5 years of operating experience. Spreader-stoker and fluidized bed combustors are the most advanced. The spreader-stoker is the only type of wood combustor currently available in larger than 200 MBtu/hr heat capacity. Fluidized bed combustors will accept the greatest variety of fuels and achieve high combustion efficiency.

The following estimated annual capital costs and 25-year Present Value (PV) life cycle costs are given for a 70 MBtu/hr (20 MW) boiler; costs are in millions of 1979 dollars:

Boiler Type	Capital Cost	Annual Cost	PV Cost
Cyclonic Combustor*	$1.15	$1.13	$16.45
Fluidized Bed	1.40	1.16	17.0
Spreader-Stoker	1.30	1.29	18.2

*Note that the cyclonic combustor fires dry sawdust.

While not as advanced as combustion-based wood fuel technology, the wood gasification and liquefaction systems will provide useful technologies in the near term. Since more than 25 manufacturers expect to be producing and selling systems by the end of 1984, there should be enough examples of wood gasification/liquefaction on line that Army planners could consider projects using those technologies for startup during 1988 through 1993 (Appendix B).

The gasification/liquefaction technology has potential application as a retrofit to be used with existing boilers. There is also potential application where an installation has a large number of decentralized boilers.

Recommendations

Army planners should consider wood combustion technology for application at installations where wood is available. Wood-based projects should be forwarded as part of the routine MCA submittals where the life cycle costs are favorable compared to coal or other nonrenewable fuels.

The Army should consider building a demonstration plant using the technologies of wood gasification/liquefaction, in order to prove the technology and gather cost data as a basis for future projects.

If the Army chooses not to build a demonstration plant, it should study the emerging wood technologies to acquire technology information and actual cost information for future energy construction planning.

APPENDIX A

EVALUATION OF COMBUSTION-BASED BIOMASS-DERIVED FUEL TECHNOLOGIES

Prepared by

Clark, Dietz Engineers, Inc.

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BACKGROUND

Motivation for this study comes from the Army's desire to find alternatives to fuel oil and natural gas for energy production. Due to increased prices and reduced availability of these fuels, they are rapidly becoming uneconomical and, in some cases, unreliable. In addition, with increased U.S. dependence on foreign oil sources, the Army could be compromising its ability to function in the event of world conflict. A conversion now to coal or renewable energy sources (solar, biomass, and wind) represents a farsighted move toward future energy security.

Coal is by far the most plentiful fossil fuel in the U.S. Using coal would help to ensure American energy independence. The drawback to this solution, however, is that much of the domestic coal reserves are high in sulfur. When burned, this coal produces dangerous sulfur oxide emissions in violation of emission standards. The additional cost required for the control of these emissions can be great enough to make energy production with coal uneconomical. Wood fuels are characteristically low in sulfur content (0.6%). This means that costly sulfur oxide control is unnecessary when burning wood.

Previous studies conducted by the Army have assessed the availability of wood fuels within the continental U.S. Their findings serve as motivation for this study which evaluates the current state of wood burning technology.

SCOPE

This study considered both new and retrofit systems for processing and burning wood fuels. Systems which utilize wood fuel in any of its solid forms and which fall into the energy production range of 3.5 to 250 million british thermal units per hour (MBtu/hr) were included. Other forms of biomass, such as peanut shells or bagasse (sugar cane wastes), were not considered although many of the systems studied are capable of handling these fuels as well. Biomass derived fuels in other than solid forms, such as alcohol, were not within the scope of this study.

The types of equipment considered were fuel preparation, handling, and burning equipment, and particulate emission control equipment. Wood harvesting equipment was not included since it is likely that the Army will not become involved with this aspect of wood fuel usage.

APPROACH

In the first phase of this study, a literature search was conducted to determine the current state of development of wood energy technologies. Also sought was any available cost information. The literature search consisted of a manual search of a few library listings and a computerized search of the NTIS*, Energyline, and Engineering Index information banks. The literature which proved useful to this study is listed in the Bibliography.

The second phase of information gathering was directed at manufacturers of wood energy systems. Specific characteristics of each of the various types of wood burning systems were determined through telephone conversations and company literature. Capital cost data were also provided by a few manufacturers.

In the third phase of this study independent organizations and users of wood energy systems were contacted in an effort to arrive at some actual operation and maintenance (O & M) costs for these systems. Organizations contacted were the Bio Energy Council, the Wood Energy Institute, and the U.S. Department of Energy.

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*National Information Service, Springfield, VA.

WOOD FUELS

Wood fuels are available in large quantity in many parts of the U.S. Any commercial operation which utilizes wood produces waste wood, and any timber which is unacceptable for commercial use can be used as fuel. Wood is low in sulfur (typically 0.6%) and therefore does not produce dangerous levels of sulfur oxides when burned, as do many fossil fuels. The flame temperature in a wood fire is lower than in a coal, oil, or gas fire; therefore; the level of nitrous oxides produced is lower. The amount of particulates produced by burning wood is somewhat less than that produced by burning coal, but is greater than that produced by either fuel oil or natural gas. Because of this, some form of particulate emissions control is required; however, relatively inexpensive mechanical collectors, such as multi-cyclones, are usually sufficient.

Wood is characteristically a less concentrated form of energy than are fossil fuels. Wood averages about 8,000 Btu/lb, whereas coal averages around 12,000 Btu/lb. On a volumetric basis, wood contains one-third the heat value of coal. This means that to supply an equivalent amount of energy, three times the volumetric fuel feed rate is required with wood as compared with coal. Fuel handling equipment will consequently be in greater use; however, it will not require proportionally higher maintenance because the lower-density wood produces less strain. The lower energy content of wood also requires more furnace volume for a given energy output. When a boiler is converted from coal to wood, it typically results in a 20% derating of the boiler.

Wood fuels exhibit a large degree of variation both in form and energy content. This is due largely to the wide variety of ways in which wood is used, and therefore, the types of waste wood created. The following is a brief description of the various types of wood fuels.

Hogged Fuel

Hogged fuel is wood, bark, or a mixture of these in the form of coarse chips. These chips can vary in size from 1/8 inch to 2 inches across and usually contain some fines. Moisture content can vary from 20% to 55% (wet basis) depending on how green the wood is and how the fuel is stored. Hogged fuels typically do not flow well, especially when wet, and require some form of agitation to prevent bridging when stored in bins or silos. Except for this, hogged fuels can be handled and burned much like coal. This form of fuel can be stored unsheltered without agglomerating, although its heating value will be less when wet.

Sawdust

Sawdust is a waste product of lumber production. Producers of sawdust are beginning to recognize it as an energy source and are burning it rather than disposing of it. For this reason, it will probably not be as commercially available as other forms of wood fuels. Sawdust normally ranges in moisture content from 10% to 50%, but can contain as much as 65% moisture if stored unsheltered from the rain. This type of fuel is usually conveyed pneumatically (in suspension with air) and burned in cyclonic furnaces.

Sanderdust

Sanderdust is also a waste product of the wood industries and is finding use as a fuel by its producers. This material is produced when kiln dried wood is finished and therefore it has a low moisture content, typically 8% to 12%. This makes it a superior fuel to sawdust if stored sheltered from the rain. Sanderdust is handled and burned the same as sawdust.

Planer Shavings

Planer shavings are produced when wood is processed into lumber. Most of it finds a market in the paper and pressboard industries. Although it is sometimes used as a fuel, it is uneconomical to transport due to its bulkiness.

Pelletized Wood

With the increased use of wood as a fuel, especially by industries not directly involved in wood products, there has developed a market for pelletized wood fuels. A few companies currently exist who market pelletized wood.

Pelletizing is a process by which the heat value and handling characteristics of wood are improved through drying and densifying. In this process, wood is pulverized into fine particles, dried, and then compressed into pellets 1/8 inch to 1/2 inch in diameter and of various lengths. The end product typically contains 10% to 15% moisture and has a heat content of 8,500 Btu/lb.

The improved properties of pelletized wood fuel allow it to be stored and burned by coal-burning equipment without modification. Manufacturers of pelletized fuel also claim that the fuel will not break down in shipment. Users of pelletized fuel indicated that a 10% to 20% breakdown does occur.

This does not adversely affect the heat content of the fuel, but it can create dust problems. Users contacted did support manufacturers' claims regarding good flow characteristics. No bridging or plugging problems were encountered.

Another advantage of pelletized wood is its consistency. Conventional wood fuels tend to vary in heat content due to variable moisture content. This can result in more difficult boiler control and, therefore, higher operation costs. The consistent nature of pelletized fuel avoids this problem.

Two main disadvantages of pelletized wood fuels are higher cost and unavailability in some areas. Most users contacted felt that pelletized fuel is not justified over hogged fuel unless the higher heat content is needed to meet load demands. A third disadvantage of pelletized wood is that it must be sheltered during storage. If the fuel becomes wet, it tends to bind together.

A recent development in wood fuels is the production of pellets which are a mixture of wood and other combustible wastes. The combustibles range from agricultural and municipal wastes to thermoplastics. These additives are claimed to improve the binding properties of the pellets and some can improve heat content. The manufacturer using the thermoplastic additive advertises a product with potential heat value of 14,000 Btu/lb.

STATE OF TECHNOLOGY

Before the widespread use of fossil fuels in America, over 80 percent of all energy consumed was supplied by renewable sources. These included wind, water, and muscle power, but the vast majority was supplied by wood. As fossil fuels became more widely used, dependence on wood fuels declined. Today this trend is starting to reverse as fossil fuels become more scarce and expensive. Wood is once again being considered as a viable source of energy.

During the time when fossil fuels have dominated, many changes have occurred in energy technology. Combustion equipment has become more automated and its combustion efficiency has been improved. Concern over reducing air pollution emissions has brought about additional modifications. Wood burning technology did not advance much during this period since wood fuels were in limited use. Within the past ten to fifteen years wood energy has received renewed interest and consequently, wood burning technology has undergone rapid improvements. Fuel preparation, handling, and combustion equipment has been developed which effectively meets today's energy requirements. There are at present many commercially available systems which burn wood fuels. Most of these have been in use for a minimum of five years.

Wood burning systems fall into five basic categories or principles of operation. The wide variety in these systems is due largely to the wide variation in wood fuels. Some systems were designed to optimally burn only one form of fuel whereas other systems were developed to accept virtually any form of fuel. The five types of systems are described below. Particulars about the sources of this information are listed in the Annex.

Dutch Oven

Dutch ovens use a form of burning known as pile burning. The wood fuel is fed from above and allowed to pile up on a stationary grate (Figure 1).* Under-fire air is supplied to partially combust, or carbonize, the fuel, thus driving off hot combustible gases. Over-fire air is mixed with these gases as they are fed into the boiler section. Here combustion is completed, producing steam in the boiler tubes.

This type of boiler was used extensively before 1950 but now is considered outdated due to its inefficient combustion and difficult control. Although some dutch ovens are still in operation, they are generally being replaced by more advanced furnaces.

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* All figure and table numbers in this appendix refer to Appendix A.

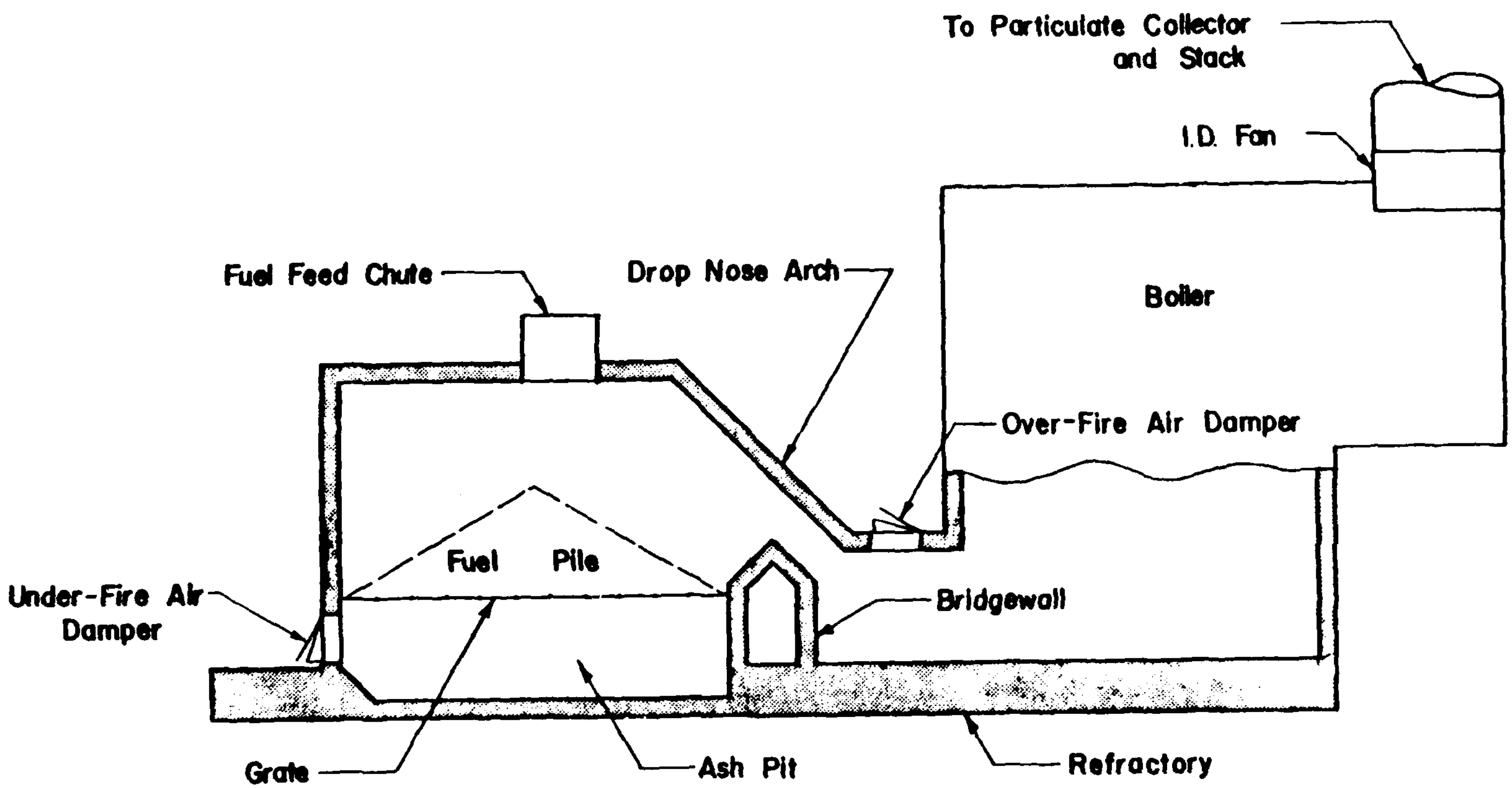

Figure 1
Dutch Oven Furnace

Conifer

The conifer is an updated version of the dutch oven. Rather than the wood fuel being piled onto a flat grate, however, it is allowed to flow down a series of stepped grates through which the primary air is fed (Figure 2). This allows for more efficient gasification and finer control since the fuel is spread in a thin layer rather than piled. As with the dutch oven, the hot gases are mixed with air, fed to the boiler section, and combusted. One manufacturer of this type of boiler claims that their unit will successfully burn wet or dry hogged wood, planer shavings, sawdust, sanderdust, wooden pellets, and bark.

Retrofit units are also available from this company which convert fuel oil and natural gas fired boilers to wood-fired units. This, of course, would require a certain amount of space at the front of the boiler for fuel feeder and burner installation. Also required would be the installation of a fuel storage silo and a mechanical particulate emission control device, such as a multi-cyclone.

A list of current installations was supplied by the manufacturer which included 15 conifer installations in 10 states.

One limitation which this type of system has is size. The literature indicated stock units were available from 0.75 MBtu/hr to 8.40 MBtu/hr heat capacity. In a telephone conversation with the manufacturer it was indicated that custom-built retrofit units could be supplied with heat capacities as high as 13.4 MBtu/hr.

Spreader-Stoker

The spreader-stoker (Figure 3) is currently the most commonly used system for burning wood fuels. In this type of boiler, the fuel is thrown onto a grate by a mechanical or pneumatic spreader. The grate can be stationary or it can be equipped for ash removal by traveling, oscillating, or dumping. Under-fire air is fed in through the grate and over-fire is supplied above it. Much of the combustion actually occurs in suspension above the grate as the fuel contacts the hot gases. Larger pieces fall onto the grate where combustion is completed. The boiler tubes are located in the furnace chamber where they are heated, both by the hot combustion gases and by radiant energy produced in the hot fuel bed.

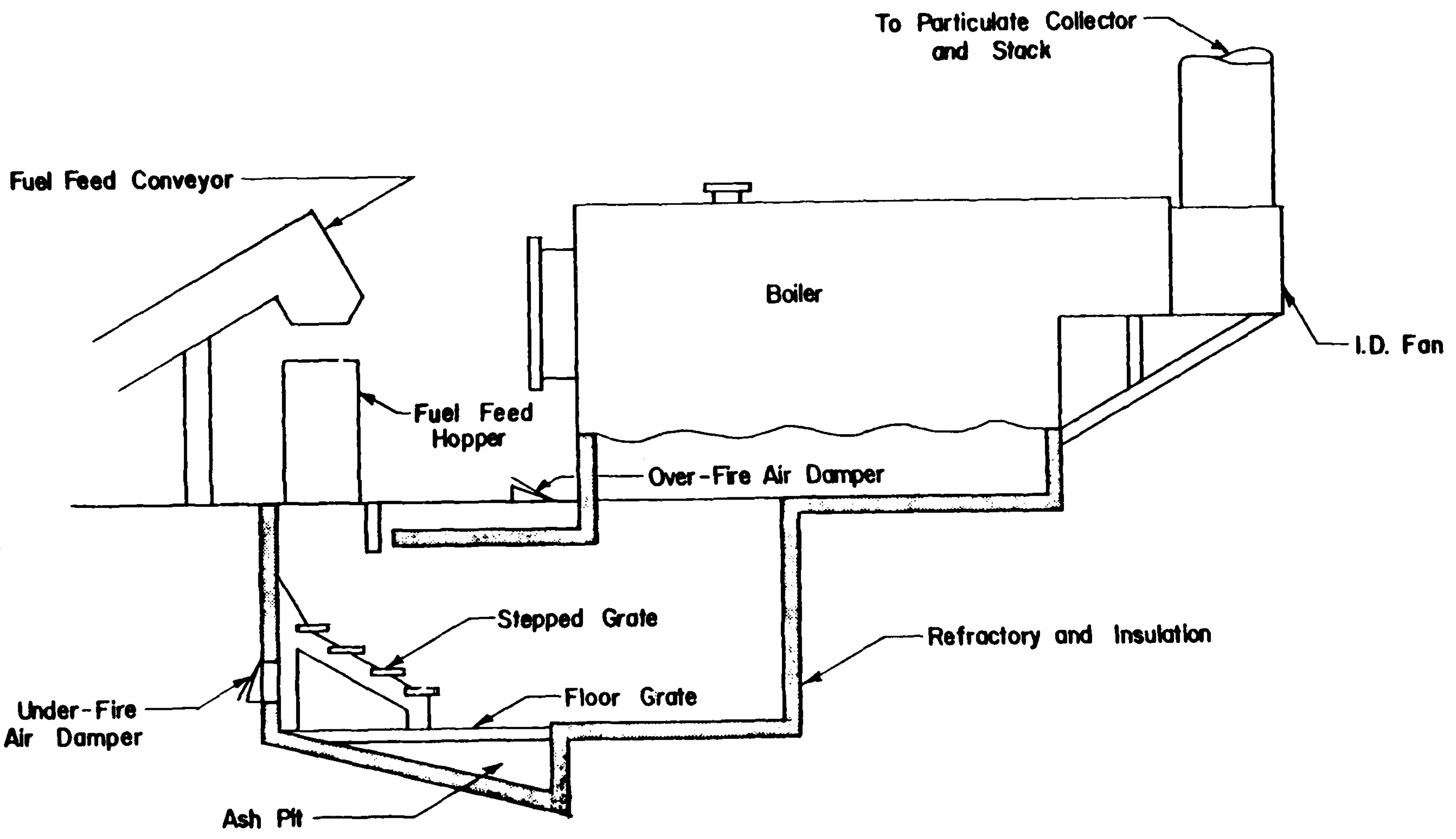

Figure 2
Conifer Furnace

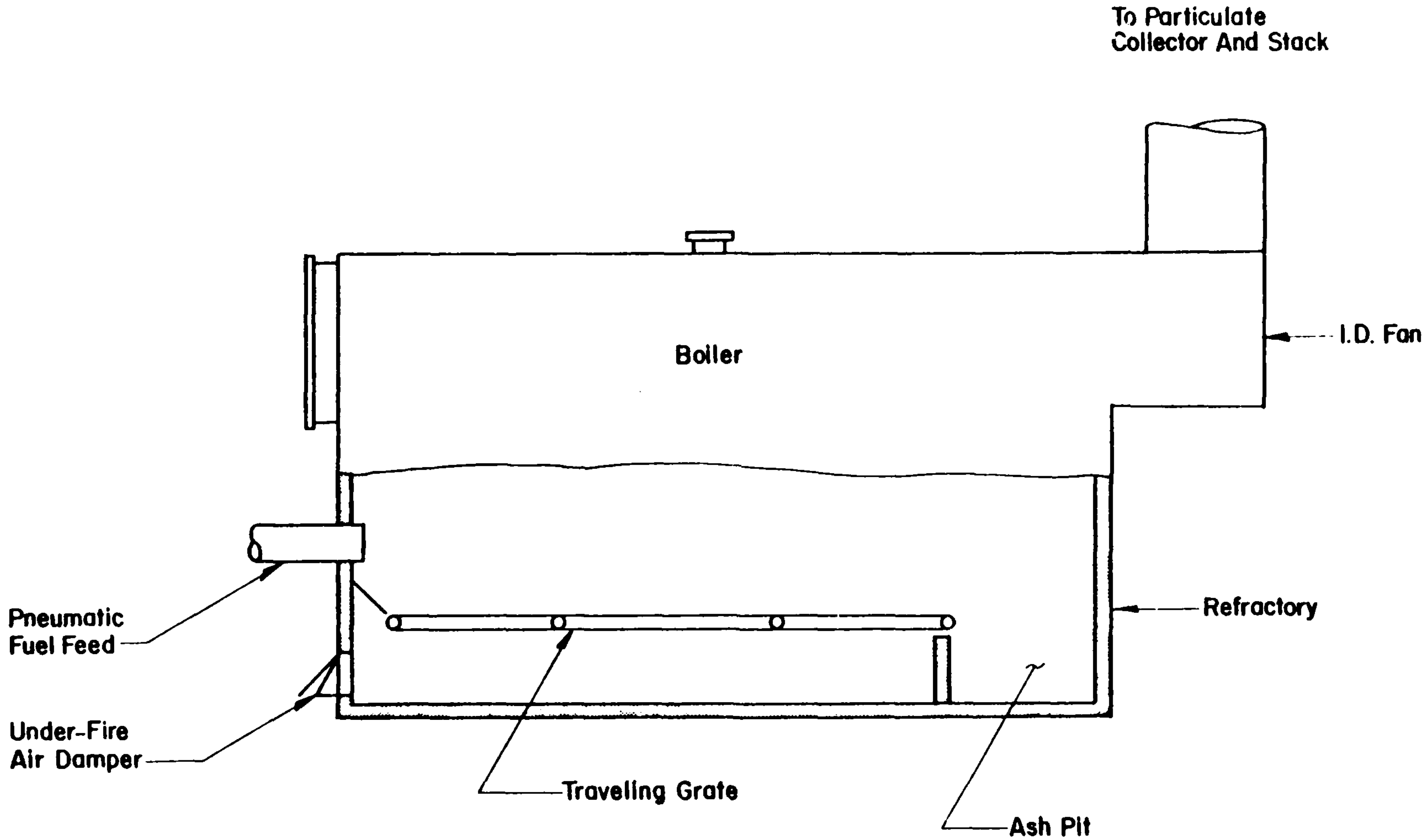

Figure 3
Spreader-Stoker Furnace

Fuels best suited for spreader-stokers are hogged fuels and pellets. Maximum allowable moisture content is 50%. Another possibility is the firing of spreader-stokers using a mixture of wood fuel and coal. The coal apparently aids in the combustion of wood because boiler efficiency is not reduced with as much as 35% by volume green wood supplement.[1] The wood aids in boiler operation as well. Decreased slagging of firewalls, decreased ash bed clinkering, decreased ash production, and improved superheat temperature stability are all observed. Due to the lower ash content of wood, the mixture produces less fly ash than does 100% coal as evidenced by longer intervals between emptying of the ash hopper. The most significant advantage, however, is the reduction of sulfur dioxide emissions. In some situations significant savings could be realized if, by using a wood fuel supplement, emission standards could be met without switching to high-priced, low-sulfur coal or installing sulfur emission control equipment. In areas where waste wood is plentiful, savings might also be realized simply because the cost of wood fuel could be less than coal on an equivalent energy basis.

Factory-assembled packaged spreader-stoker boilers are available up to 75 MBtu/hr capacity and field-erected units can produce as much as 600 MBtu/hr. Coal-fired spreader-stoker systems can be fired on wood fuel with little modification. Fuel storage equipment will operate using pelletized fuel without alterations, but will require the addition of agitation equipment if hogged fuel is used. Coal transporting conveyors will handle wood fuels, although pneumatic systems are usually installed to reduce dust and maintenance requirements. Modifications to the boiler itself are typically only operational. Since wood has a lower ash content than coal, ash bed depth is less, which causes higher grate temperatures. To prevent overheating of the grate, under-fire air is usually increased or grate travel speed is reduced to allow greater ash build-up. Although a coal boiler can be converted to wood with these modifications, it is not without some derating. The energy content of wood can be somewhat lower than that of coal; consequently, the maximum energy capacity of the boiler will be reduced.

Converting an oil or gas-fired boiler to spreader-stoker operation is not considered to be practical. Extensive furnace modification is required and substantial derating of the boiler results. If retrofit of an oil or gas boiler is desired, other types of wood furnaces, such as conifers or fluidized-bed combustors would be a better choice.

Fluidized Bed

A relatively new advancement in wood-burning technology is fluidized bed combustion (Figure 4). In this process, the combustion and heat exchange functions are separated. The combustion takes place in an inert bed of sand or small pebbles which is fluidized (suspended) by air forced from below. Fuel is fed from above and is preheated and partially combusted by the hot combustion gases before falling into the bed where combustion is completed. The bed acts to stabilize the process by transferring the motive force from the air flow to the various sized fuel particles and also stores thermal energy to sustain combustion. Impurities such as ash and contaminants are continuously removed by screening a bleed stream of the bed media, after which the media is returned to the bed. The hot combustion gases are piped to an adjacent heat recovery boiler for steam production. Start-up of a fluidized bed combustor is achieved using an auxiliary fossil fuel such as fuel oil or natural gas to pre-heat the bed.

Until recently, these combustors were available only in packaged units no larger than 40 MBtu/hr heat output. Further developments, however, have made practical the production of field erected units as large as 160 MBtu/hr.

Since the furnace and boiler are separate units, this type of system lends itself well to retrofit applications when converting from fuel oil or natural gas. The fluidized combustor can be mounted some distance from the boiler, and be connected to it with insulated ducting. If boiler house space is limited, it would even be possible to locate the furnace in a separate building adjacent to the boiler house and pipe the heat over to the existing boiler steam production. This type of retrofit would be rather expensive, however, due to the length of high temperature ducting required. The existing oil or gas burners could be left intact as a backup in the event of delayed wood fuel shipments.

A major advantage of fluidized bed combustors is the variability in fuels which it will accept. Virtually any wood fuel from sawdust to 2-inch diameter hogged fuel and from 10% to 60% moisture content can be burned. Impurities such as sand or dirt are also tolerated better by fluidized bed combustors than by any other wood-burning furnaces. This type of furnace is also typically a high-efficiency combustor. Due to the vigorous mixing and long residence time, essentially complete burnout of the fuel is achieved.

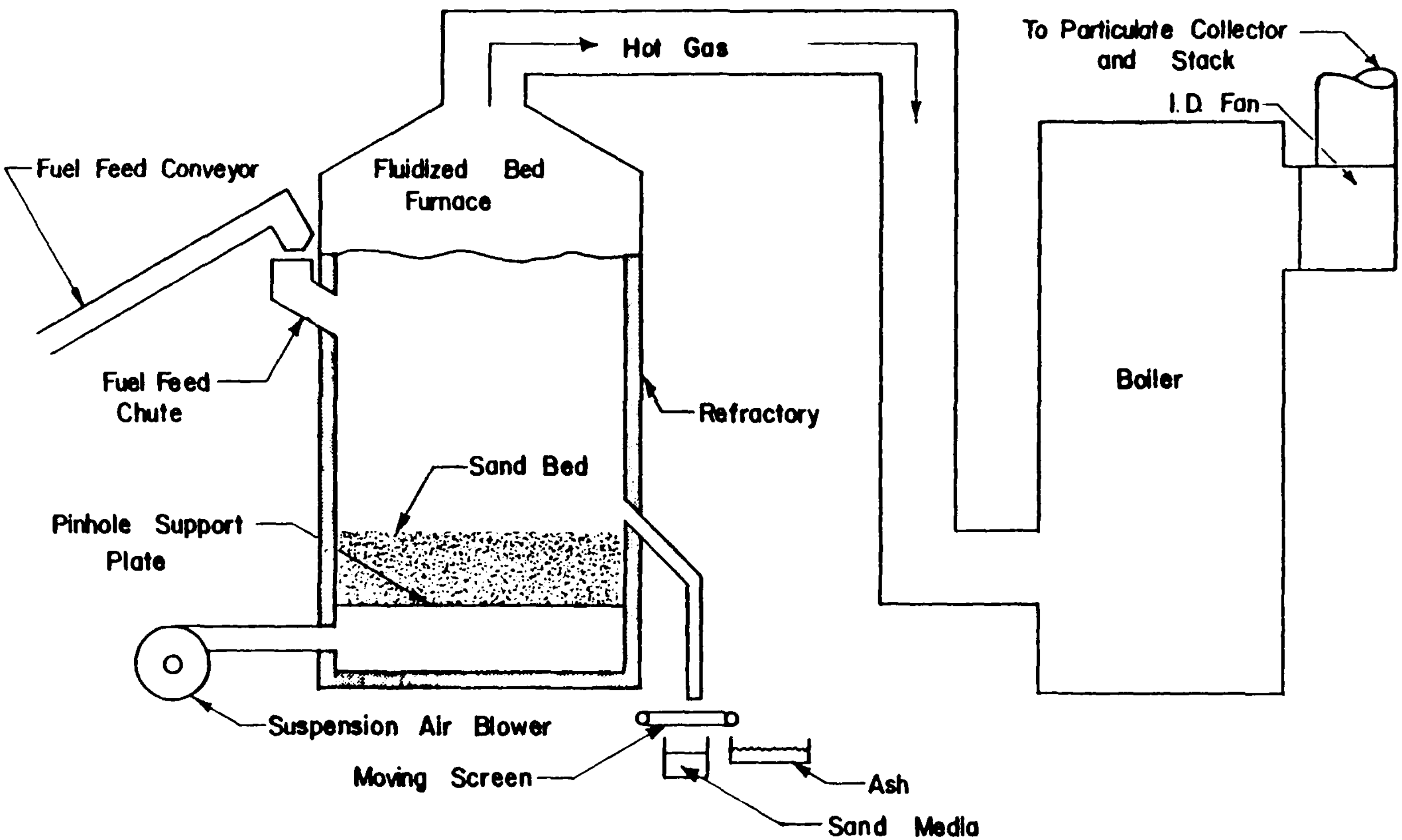

Figure 4
Fluidized Bed Furnace

Disadvantages of fluidized bed furnaces are high electrical energy consumption and limited size. A typical power requirement for suspension of the bed is 50 Hp for a 12 MBtu/hr furnace. This represents a 15% parasitic power demand not including support equipment. The largest fluidized bed combustor believed to be available is 160 MBtu/hr. Further developments could make larger units practical in the future.

Cyclonic Combustor

A cyclonic combustor, also known as a forced vortex combustor, represents another relatively new advancement in wood-burning technology. This type of burner was developed for a very specific purpose: combustion of waste sawdust and sanderdust. For this reason it is more limited in application than are other wood furnaces. It will accept only dry (15% maximum moisture content), pulverized (1/8-inch diameter or smaller) fuel.

In this type of combustor, the fuel is pneumatically fed in at one end of a refractory lined cylinder (Figure 5). Combustion air is forced into the cylinder tangentially through many ports in the refractory, creating a violent swirling action. The fuel is burned while in suspension, forming hot gases which are fed out the far end of the burner to a heat recovery boiler for steam production.

Like the fluidized bed combustor, the cyclonic combustor is an efficient heat producer and can be retrofitted onto some existing boilers. The cyclonic combustor also has higher electrical power demands than do more conventional wood burners, however not as great as fluidized bed combustors.

The greatest disadvantage to cyclonic combustors is, of course, the limited forms of fuel it will accept. If, however, a dependable supply of sanderdust, planer shavings, or dry sawdust is available, this type of burner should be considered a prime candidate.

Support Equipment

In general, when an engineering firm or equipment manufacturer designs a wood-burning system for a specific application, they concern themselves with the entire process from fuel storage through emission control. The support equipment such as silos, conveyors, ash-handling equipment, and particulate collectors are all proven technology and do not vary significantly from system to system.

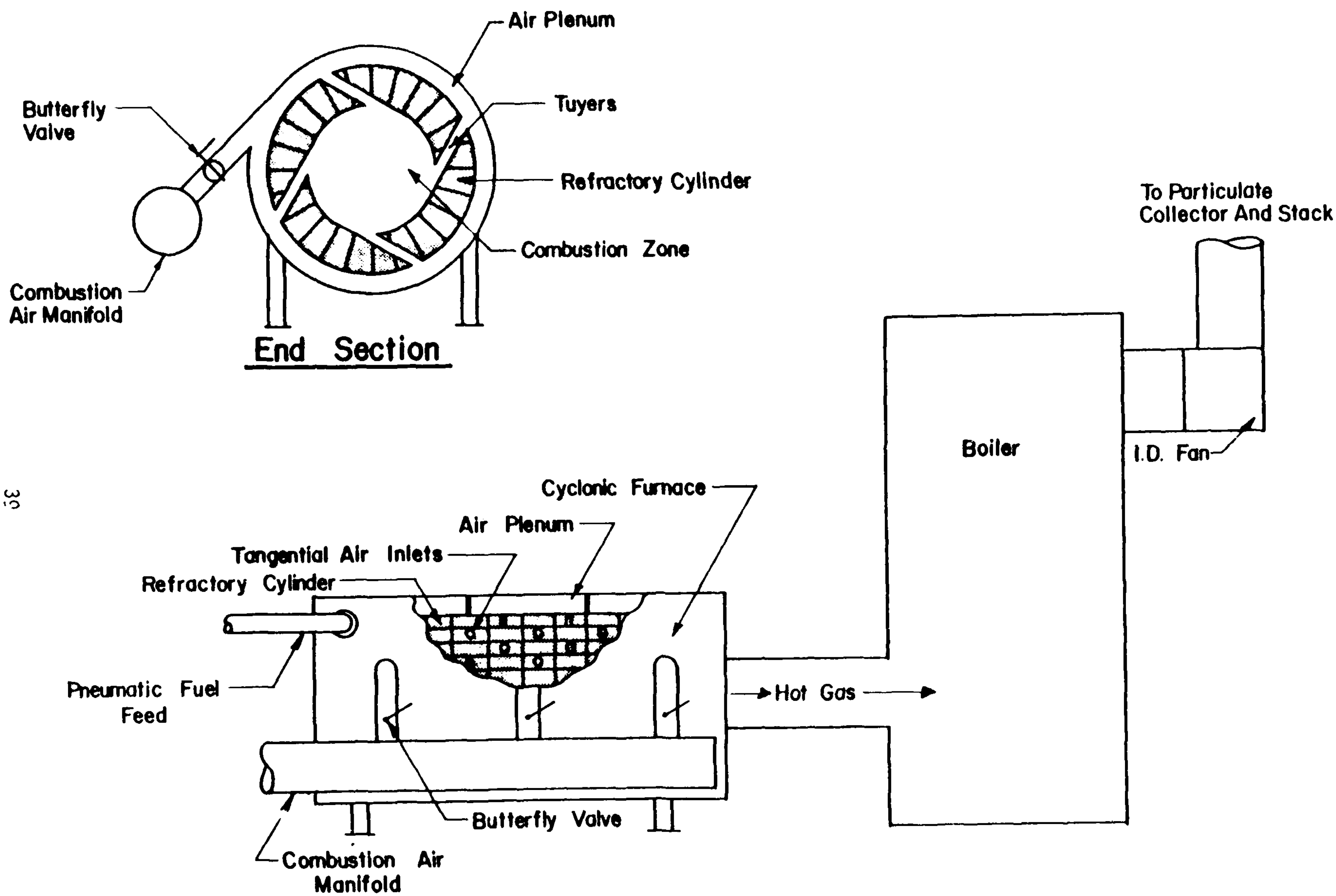

Figure 5
Cyclonic Furnace

The most commonly used method for conveyance of wood fuels is pneumatic tubing. In this type of system the fuel is metered into a stream of moving air and transported by it. When the fuel/air mixture reaches the furnace, it is usually blown in above the fuel bed to achieve fuel drying and preheat as well as to mechanically spread the fuel. Alternative transport systems are screw and belt conveyors similar to those used for coal handling. These are not as widely used due to dust problems and higher maintenance requirements.

Wood fuel storage silos and bins typically contain agitators or augers to promote fuel unloading. Without such devices the fuel tends to bridge, which stops flow. The agitators are simple and do not require excessive amounts of power, but are necessary, especially when wet fuels (greater than 20% moisture) are stored.

Particulate emission control is generally achieved using a multi-cyclone. This is a mechanical collector with no moving parts. It is the simplest and lowest maintenance particulate collector available and therefore has the lowest operation and maintenance costs. Some manufacturers use baghouses or electrostatic precipitators instead, which achieve better particulate collection but which have higher capital and annual costs. If local emission standards can be met using a multi-cyclone collector, it would be the preferred method.

On-site fuel preparation equipment is sometimes included as support equipment when fuel is available only in an unusable form, such as logs or blocks. Hoggers, pulverizers, and pelletizers are examples of such equipment. Hoggers chip logs or blocks into smaller pieces (maximum 2 inches across) which are more easily handled and burn more readily. Pulverizers produce a very fine powderlike fuel which can be dried rapidly and used in cyclonic combustors, or mixed with fuel oil and burned in a conventional oil-fired furnace. Pelletizers dry and densify the fuel to increase its volumetric heat content and to make it more easily handled by conventional coal-firing equipment.

Since these fuel conditioners can add considerably to the operation and maintenance costs of a boiler house, it would be advisable not to include them in a wood-fired system unless it can be justified economically. On-site pelletizing would be justified only if the required boiler energy output could not be achieved without it. Converting from coal to wood firing typically results in a 30% boiler derating. If this cannot be tolerated, pelletizing can improve this to perhaps only a 10% derating through densification and drying of the fuel. It must be realized that pelletizing consumes energy, typically 15% of what it processes. A fuel with higher heat content is produced; however, additional energy input is required, typically electrical and additional wood fuel. On-site pelletizing will increase boiler rating, but it will also increase electrical and fuel consumption.

A few companies already exist which will supply pelletized wood fuel under contract agreement. If no such supplier is located within 300 miles of the boiler house, however, the transportation costs begin to offset the cost benefit of wood fuels over fossil fuels. One possibility would be to enter into a long-term agreement (10 years) with a pelletized fuel supplier to encourage them to build a wood-pelletizing plant near the Army boiler plant. If the Army would agree to purchase one-half to two-thirds of the pelletizing plant's potential output, the company could develop additional markets for its fuel within the area with the remaining fuel produced. In this way the company could become established in that area and could ensure its continuation after the termination of the Army contract. This should provide additional incentive for establishing a pelletizing plant.

The benefit to the Army from establishing such an agreement would be a reliable source of a clean and fairly high grade fuel. If the boiler being supplied is coal-fired, very little modification would be necessary. This would reduce conversion costs considerably and would permit the continued use of coal as a backup.

ECONOMICS

To date there has been little, if any, detailed cost data collected for burning wood fuels. The vast majority of wood fuel users are producers of lumber or other wood products and who therefore generate large quantities of wood wastes. The incentive for burning wood fuel comes as much from the need to dispose of a waste as it does from the need for lower priced fuel. In many cases the waste represents a loss to them when having to dispose of it, so by utilizing it to produce energy they receive a double benefit. Typically, the cost of converting from fossil fuels to wood is recouped within a year under these circumstances. For these companies, performing detailed economic analyses or operation and maintenance (O & M) cost monitoring is not justified since the savings in fuel cost alone is so substantial that it greatly overshadows any increase in operation or maintenance costs. The decision to convert to wood fuel is made on the basis of fuel costs alone.

The same is true of many of the commercial consumers of wood fuels; that is companies not directly involved in the wood industries who must purchase wood fuel as they would any other fuel. The decision to convert to wood is typically made on the basis of fuel cost alone without detailed consideration for effect on O & M costs. Once the conversion is made, records are not kept for assessing the impact on overall costs. In other instances the decision to convert to wood fuel is made on the basis of availability and long-term energy security. Fossil fuels (especially natural gas) are becoming less available in many parts of the U.S., and in some of these areas, renewable sources of wood fuel are readily available. The decision to switch is motivated by supply rather than cost. In these cases, too, it is unnecessary to keep accurate account of the effect on O & M costs, since cost was not the motivating factor.

A few studies have been conducted which evaluate the economics of converting to wood fuel for a specific installation. These use the local prices for wood and fossil fuels and make certain assumptions as to operation and maintenance labor requirements. One such study conducted for the Appalachian Regional Commission is entitled "The Feasibility of Generating Steam in West Alabama Using Wood as a Fuel, Veteran's Administration Hospital".[2] The economic analysis indicated an annual savings of $7,000 in fuel costs when compared with natural gas for a 60 M Btu/hr heating plant which operates intermittently. This savings, however, is offset by estimated annual increases in operation labor of $10,000, in power consumption of $10,000, and in maintenance labor of $6,000. The end result is an overall annual loss of $19,000 by switching to wood. In the economic summary section of the report, it is stated that the apparently poor economic picture is a result of the artificially low (government-regulated) price for natural gas which the hospital pays. If deregulation of this price were to occur and the hospital were forced to pay what others in that area pay, wood fuel would become competitive. The report goes on to state in the findings section that a switch to wood fuel at this time might still be advisable in the light of likely future natural gas price increases.

A more recent publication entitled "Biomass Energy Success Stories" produced by the Bioenergy Institute[3] describes many case histories where wood fuel has proven to be economical. Most of these do not list individual cost items but present the costs simply as fuel costs or as a sum of all costs. It appears from these case histories that the effect on O & M costs of converting to wood fuel is insignificant when compared with the effect on fuel costs, even for commercial wood fuel purchasers. It must be realized that most current wood fuel is derived from wood wastes and, therefore, is quite inexpensive. As markets for wood fuels are developed, the prices will undoubtedly increase. Since wood is a renewable resource, however, it should not experience the dramatic price increases which expendable fossil fuels have experienced and will likely continue to experience in the future.

None of the manufacturers of wood-burning boilers who were contacted for this study had any O & M cost information. A few stated that costs should be of the same order as those for coal-fired equipment.

Capital costs for wood-burning systems range between $10 and $20 per pound of steam per hour capacity, depending on size and complexity. Usually each system is engineered to fit a specific application; therefore, manufacturers are hesitant to quote prices. This is especially true for a retrofit application. One manufacturer did provide a firm estimate, however, of $1,300,000 for a new wood-burning system with a capacity of 70 MBtu/hr completely installed. This estimate included fuel- handling equipment, a spreader-stoker water tube boiler, and a multi-cyclone for particulate emissions control. This price translates into $18.57/lb steam/hr capacity, which is toward the upper end of the price range, but still within it. The date of the quotation was June 29, 1979. The manufacturer thought that O & M costs for this system would be slightly less than for a comparably sized coal-fired unit due to the lower ash content of wood.

The Burlington Electric Department in Burlington, Vermont is one of the few utilities in the U.S. to convert to wood fuel. The conversion took place early in 1978, before which coal was burned. Because the conversion was from coal, the costs were low. To convert 100 MBtu/hr of boilers, the cost was $50,000, half for equipment and half for labor. Maintenance costs have been reduced 25-30% due to the lower density and ash content of wood. Operation of ash equipment was also reduced due to less ash production. Boiler operation remained about the same. These were all offset, however, by an increase in the cost of operating the fuel-handling system. Due to the low volumetric energy content of wood, the fuel feed system is being operated almost constantly, resulting in doubling the operation cost for this system. The utility representative said it would be difficult to accurately separate the individual cost items; however it was believed that the overall O & M costs for wood burning were fairly similar to those for coal burning.

Although very limited cost data are available for wood-burning boilers at this time, estimates can be made based on system complexities and operational requirements. Table 1 is a compilation of estimated cost data for the systems discussed in this report.

The basis upon which these figures were determined was a new installation, fired on hogged wood fuel, with an output capacity of 70 MBtu/hr. The capital costs include secondary fuel storage bins, fuel-handling equipment, burner and boiler, induced draft fan, and multi-cyclone particulate collector, all installed. Assumptions for each of the annual cost categories are listed below the table.

Retrofit installations typically have lower capital costs, but can approach the cost of a new installation if modifications are extensive. If wood fuel is not available in a readily burnable form, additional costs would have to be added for capital and O&M of a hogger, pelletizer, or pulverizer as indicated in Table 2. If the type of fuel used requires covered primary storage, this cost must be added. In locations where the multi-cyclone cannot reduce particulate emissions to within standards, additional capital as well as O&M costs must be included for a baghouse or ESP collector. The costs associated with support equipment, such as the boiler house structure or the boiler water treatment system, were not included in these figures.

TABLE 1

ESTIMATED COSTS FOR WOOD-BURNING BOILERS ($\$ \times 10^3$)

	Dutch Oven[1]	Conifer[1]	Spreader-Stoker	Fluidized Bed	Cyclonic Combustor
Capital Cost	950	1,000	1,300	1,400	1,150
Annual Costs					
Operation Labor	325	290	365	305	260
Maintenance	28.5	30.0	39.0	42.0	40.5
Electric Power	17.5	19.0	20.0	67.5	55.0
Fuel	1,050	920	865	750	775
Auxiliary Fuel	--	--	--	0-7[2]	0-4[2]

1 These figures were extrapolated from the largest available units.

2 Depending upon number of start-ups per year.

Assumptions

General:
70 MBtu/hr heat output at design capacity
Boiler operating at 80% of design capacity 8,400 hours per year

Operation Labor:
Includes fuel handling and boiler operation
$12/hr labor rate
1.3 multiplier for benefits

Maintenance:
Includes labor and replacement parts
3% of capital cost

Electric Power:
$.04 per kilowatt-hour

Fuel:
$25/ton
8,000 Btu/lb heat content
Cost varies due to conversion efficiency for each type of burner

Auxiliary Fuel:
Fuel oil at $1.00/gallon

TABLE 2

ESTIMATED COSTS FOR WOOD FUEL PROCESSING EQUIPMENT ($\$ \times 10^3$)

	Hogger	Pellitzer	Pulverizer
Capital Cost	300	850	500
Annual Costs			
Operation Labor	130	260	130
Maintenance	9.0	25.5	15.0
Electric Power	50	175	100
Fuel	--	315	--

Assumptions

General:
70 MBtu/hr fuel output at design capacity
Unit operating at 80% of design capacity 8,400 hours per year

Operation Labor:
Includes fuel handling and boiler operation
$12/hr labor rate
1.3 multiplier for benefits

Maintenance:
Includes labor and replacement parts
3% of capital cost

Electric Power:
$.04 per kilowatt-hour

Fuel:
35% of feed wood consumed for drying product
$20/ton unprocessed fuel cost

It must be remembered that the cost figures in Tables 1 and 2 are estimates and therefore, cannot be applied in all cases. Each installation of a wood-burning boiler is unique, and local conditions of fuel supply, labor rates, and power costs will dictate the actual economic outlook for wood fuel use at that installation.

CONCLUSIONS

Combustion-based wood fuel technology is well established in this country. Experience with burning wood dates back before the use of fossil fuels and renewed interest in wood energy has spurred significant advances.

The five categories of systems evaluated by this study are all commercially available with five or more years of operating experience. Of these, the spreader-stoker, fluidized bed combustor, and cyclonic combustor are the most advanced. The spreader-stoker is the only type of wood combustor currently available larger than 200 MBtu/hr heat capacity. Fluidized bed combustors will accept the greatest variety of fuels and achieve high combustion efficiency. Cyclonic combustors are best suited for burning sawdust or planer shavings.

Cost data on wood-burning systems is scarce because the primary users of wood fuels are producers of wood wastes who converted to wood fuel as much to dispose of a waste as to produce inexpensive energy. Any increase in operation and maintenance costs which might have resulted is greatly overshadowed by reduced fuel costs. Because of this, no detailed operation and maintenance cost data are typically collected under these circumstances.

Any decision to convert to wood energy should be based on specific estimates for retrofitting that particular installation. The type of system best suited for any one installation will vary according to existing boiler house equipment and types of wood fuels available. For this reason no one conclusion can be stated in regard to the economics of converting to wood fuels which will hold true for all cases.

Due to the lower sulfur and ash contents of wood fuels, and the renewable nature of these energy resources, combustion-based wood utilization is worthy of consideration wherever wood fuels are available.

ANNEX

Information Sources

Source	Date	Subject	Comments
American Fyr-Feeder Engineers. Des Plains, Ill. (312)298-0044	6/05/79	Conifer	Retrofits available. Multi-cyclone supplied with unit. 1 MBtu/hr retrofit costs \$100,000.
Foster Wheeler Energy Corp. Dist. sales Chicago, Ill. (312)726-8673	6/05/79	Spreader-Stoker	20-650 MBtu/hr capacity. Will burn hogged fuel, coal, or mixture. \$15 per lb steam capacity capital cost.
E. Keeler Co. Williamsport, Penn. (717)326-3361	6/06/79	Stationary grate wood-burning boilers	10-200 MBtu/hr capacity. Stoker supplied by others. Costs not available.
Energex Limited Memphis, Tenn. (901)345-5930	6/06/79	Cyclonic combustor	1/8" max. fuel size. 15% max. fuel moisture. 45 MBtu/hr unit costs. \$300,000 without support equipment. 100 Hp combustion air blower.
Deltak Corp. Morton Grove, Ill. (312)965-1421	6/06/79 6/29/79	Spreader-Stoker	Wood or coal capabilities. 70 MBtu/hr complete system $\$1.3 \times 10^6$ installed.
Industrial Boiler Thomasboro, Ga. (912)226-3024	6/19/79	Spreader-Stoker	0.2-2.5 MBtu/hr capacity. Hogger and multicyclone supplied with unit. 4:1 turndown ratio.
York-Shipley York, Penn. (717)755-1081	6/20/79	Fluidized Bed	10-60 MBtu/hr capacity in packaged units. Will retrofit. 27 systems in operation for 5 years or more.

Source	Date	Subject	Comments
Bio Energy Council Washington, D.C. (202)833-5656	6/20/79	Wood Energy	Gave information concerning Wood Energy Institute and DOE Studies.
Wood Energy Inst. Camden, Maine (207)236-4841	6/21/79 7/12/79 1/08/80	Wood Energy	No detailed cost information available. Gave information about Morin Generating Plant conversion to wood.
U.S. Dept. of Energy Washington, D.C. (202)376-1971	6/21/79	Wood Energy	Some cost studies in progress by MITRE Corp. Available in approximately one year.
Burlington Elec. Dept., Burlington, Vt. (802)658-0300 Ext. 31	7/18/79	Conversion of Morin Generating Plant to wood fuel	$50,000 to convert 100 MBtu/hr of boilers. 25-30% reduction in maintenance. Operation cost increased about same amount.
Guarantee Fuels Independence, Ks. (316)331-0027	6/20/79	Wood Pellets	40 lb/cu ft, 12% moisture. 2,000 for a 300 ton/day plant (200 MBtu/hr output) 35% of wood burned to dry product.

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1. Grand Haven Board of Light and Power, "Supplemental Wood Fuel Experiment", Jan. 1978.

2. Russel, Benjamin, "The Feasibility of Generating Steam in West Alabama Using Wood as a Fuel, Veterans Administration Hospital", Energy Conservation Company, Sept. 1976.

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Furman, Lloyd H., "Wood Residue for Veneer Drying, A Case History", Forest Products Journal, Sept. 1976.

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APPENDIX B

AN EVALUATION OF INSTALLATION-SCALE TECHNOLOGIES FOR PRODUCING AND USING GASEOUS AND LIQUID FUEL FROM BIOMASS

Prepared by

SCS Engineers, Inc.

CONTENTS

AN EVALUATION OF INSTALLATION-SCALE TECHNOLOGIES FOR PRODUCING AND USING GASEOUS AND LIQUID FUEL FROM BIOMASS

1 INTRODUCTION

Objective

This report describes the current commercial state of the art in thermochemical biomass conversion, specifically those installation-scale systems capable of converting wood and wood wastes into a liquid or gaseous fuel. Throughout this report, installation-scale refers to systems with output capacities between 3 MBtuh* and 250 MBtuh. The resultant product is intended for use as a substitute fuel in process steam or hot water boilers, including those designed for such fuels, as well as for conventional oil, gas, or coal-fired boilers.

Approach

The initial stage of the investigation involved a review of pertinent and available literature. In all, over 100 articles, reports, books, studies, proceedings, and directories were evaluated. From the literature, a list was made of the more than 55 companies that were mentioned as having done or presently doing work, as having developed or marketed a product, or as having considered entrance into the field of biomass conversion (see Annex B). Canadian and U.S.-based organizations were contacted by telephone, when possible. Each contact was requested to provide information pertaining to its activities in gasification. A "fact sheet" was drawn up to assist the researcher in obtaining the information.

The results of these telephone interviews appear in Section 4 as a summary of related activities for 30 gasification vendors and researchers. A biomass conversion system was determined to be commercially available, based upon the telephone inquiries, published literature, and documented experience at both the pilot and full scales. The results of this evaluation formed the basis for recommendations as to Army applicability.

Scope

This report reviews available literature on the subject of biomass conversion, and summarizes the characteristics of available systems (e.g., output, operating range, degree of commercialization, capital and operating costs, and applicability to Army needs). However, it does not

* Million British thermal units per hour.

investigate forest harvestation, or the management or equipment used for such. Sufficient supplies of biomass feedstock are, of course, a prerequisite when considering biomass conversion.

2 HISTORY AND STATUS OF BIOMASS GASIFICATION TECHNOLOGY

The development of gasification systems began in Europe around 1840[1]. The first stationary gasification reactor was developed by the Siemens Brothers in 1857 for the conversion of coal[2]. Development of technology continued through the 1920's, using a variety of feed fuels which included biomass. Interest in gas-producing systems declined rapidly when supplies of oil became available in quantities and at costs that forced industries to choose oil over gas as the major source of energy. Before this changeover to oil occurred, gas had had many industrial applications, the most common of which were in engines and boilers, and as fuel for the brickmaking and metallurgical industries. There were a number of equipment manufacturers who produced gasifiers in addition to the engines which operated on the gas product[3].

The availability of oil-derived fuels has been the biggest single factor controlling the interest in gasifier technology. When the petroleum industry expanded during the 1920's, and oil became the chief source of industrial energy, the conversion process declined in usage. A few units were operated in areas where transportation of oil was difficult and where biomass was readily available, such as in remote mining or milling regions.

Interest in gasifiers was revived during the 1940's, again due to the availability of oil. World War II caused a decline of oil supplies, especially for nonmilitary uses. Sweden was particularly affected, and much of the gasifier development occurred there as a result. The rise in gasifier usage in Sweden was dramatic. From 1939 through April 1940, 3,100 gas producers were manufactured, approximately 1,000 of which were installed on automobiles[4]. That year, the ration of gasoline for civilian vehicles stopped completely, and a huge increase in gas producer usage resulted. By March 1941, 40,000 vehicles were operated on woody biomass gasifiers. Three months later, in June, there were 50,000, and

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1 R. Overend, "Wood Gasification an Old Technology with a Future?" Presented to the Biomass Institute, October 1977, in *Proceedings: Forest and Field Fuels* (The Biomass Energy Institute, Inc., 1977), p XX-1.

2 B.C. Horsfield, "History and Potential of Air Gasification," in *Retrofit '79: Proceedings of a Workshop on Air Gasification* (The Solar Energy Research Institute, 1979), p 4-1.

3 Overend, p XX-11.

4 Solar Energy Research Institute, *Generator Gas: The Swedish Experience from 1939-1945*, SERI/SP-33-140 (N.T.I.S., January 1979), p 9.

by July there were 60,000. This growth rate would have continued, except that shortage of tires and lubricating oil forced a restriction in the use of private vehicles[5]. However, by December of 1941, there were 71,500 gasified vehicles in Sweden. The types of vehicles using gas producers included cars, trucks, buses, boats, tractors, road rollers and graders, trains, and many types of stationary engines[6].

From the end of World War II through the early 1970's, interest in gasifiers again diminished worldwide. Overend[7] reports that the commercial production of gasifiers was abandoned by the mid-1950's, although a few manufacturers continued to market gasifiers throughout this time period[8]. A good barometer of related research activities (and, therefore, of the interest in gasification) is the number of citations in the literature. Chemical Abstracts, for example, shows 22 citations for the 10 years between 1917 and 1926; 22 between 1927 and 1936; 72 for 1937 to 1947; 11 during the 1950's; and 14 for 1957-1967[9].

The Arab oil embargo of 1973 was the impetus for the "rediscovery" of gasification as an energy source. Because of the 1973 embargo, many organizations have been involved in gasification research. Some of these groups have worked to demonstrate the applicability of the gasification process to a particular feedstock; others have been involved in primary research.

A major effort of these research organizations is to update the technology of gasification. There are many areas in which modern materials and control techniques can have a large impact on the performance of a gasifier. Work in catalysts, fluidized beds, high-pressure and oxygen-blown gasification, plant genetics, and forest management practices greatly contributes to the base of information, and has direct impact upon process improvement.

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5 *Generator Gas: The Swedish Experience*, p 9.

6 *Generator Gas: The Swedish Experience*, p 170.

7 R. Overend, "Wood Gasification an Old Technology with a Future?" Presented to the Biomass Institute, October 1977, in *Proceedings: Forest and Field Fuels* (The Biomass Energy Institute, Inc., 1977), p XX-1.

8 Personal Communication, J.S. Eck, Wilputte Corporation (June 26, 1979), and William Trethaway, Nichols Engineering (June 20, 1979).

9 R. Overend, "Gasification - An Overview," in *Retrofit '79: Proceedings of a Workshop on Air Gasification*, SERI/TP-49-183 (The Solar Energy Research Institute, 1979), p 3-2.

Within the last year alone, there has been an escalation in bio-energy-related research. Evidence for this is the Bio-Energy Directory[10], "an ongoing inventory study of biomass-related activities,"[11] which shows a two and one half fold increase in entries from the 1978 to the 1979 edition.

At present, the most readily applicable areas of gasification technology are the production of industrial process heat steam or hot water, and the use of small gasification units in combination with dual-fueled engines for producing electrical or mechanical energy[12]. Mobile vehicle applications, while possible, do not lend themselves to gasification as readily as do industrial heating applications. The time and effort needed to convert a natural gas-fired boiler to generated gas are not expected to present any major difficulties. Talib[13] estimates the cost of converting a 100,000 lb/hr steam boiler to be $4,000,000, which would include all needed equipment. The State of California is planning to convert its central heating and cooling plant in Sacramento to gasification[14]. The boilers now use approximately 120 million ft^3 (3.94 million cm^3) of natural gas per year, all of which would be replaced by the gasified wood fuel. Rockwell International is using a pyrolytic conversion system at its Marysville, Ohio, plant, and is saving an estimated $100,000 per year in fuel and trash removal costs[15]. There are many more illustrative examples of bioconversion systems through which industry has gained both economic and environmental benefits[16].

In summary, more work is required to bring biomass gasification technology up to modern standards. For particular industrial needs, (e.g., heating, cooling and steam generation), biomass gasification

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10 *The Bio-Energy Directory* (The Bio-Energy Council, June 1978), p 85.

11 P.F. Bente, Jr., *The Bio-Energy Directory* (The Bio-Energy Council, May 1979), p ix.

12 R.A. Ashworth, "Programs to Accelerate Development of Wood Gasification - Session #6," *Industry/Utility Applications - Wood Combustion Workshop* (Davy Power Gas, Inc., May 1979), p 2.

13 R.A. Ashworth, "Programs to Accelerate Development of Wood Gasification - Session #6," *Industry/Utility Applications - Wood Combustion Workshop* (Davy Power Gas, Inc., May 1979), p 2.

14 Personal Communication, Richard C. Lang, California Energy Commission (July 11, 1979).

15 Personal Communication, Bill Smith, Rockwell International, Marysville, Ohio (June 19, 1979).

16 Biomass Energy Institute, "Biomass Energy Success Stories: A Portfolio Illustrating Current Economic Uses of Renewable Biomass Energy" (U.S. Department of Energy, Contract No. EG-77-X-10-0285, March 1978), pp 5-44.

equipment is commercially available. However, there are technical, economic, and institutional barriers which hinder the commercialization of biomass gasification technology[17].

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[17] D. Klass, "Barriers to Commercialization of Biomass Energy Technology," *Summary of Remarks Presented at Mid-American Biomass Energy Workshop* (Purdue University, May 1979).

3 REVIEW OF CONVENTIONAL AND EMERGING BIOMASS GASIFICATION SYSTEMS

It was noted in the preceding chapter that numerous public and private organizations are pursuing the commercialization of their own biomass gasification technologies. This chapter presents a summary review and evaluation of these systems. Particular emphasis has been placed on the present and near-term commercial potential of each system. For this reason, those organizations conducting primary research alone have been omitted. Criteria for classifying and comparing the processes were developed as the investigation proceeded.

For the purpose of this report, a unit is considered commercially proven if it has been in operation successfully on a continual basis at some site other than the manufacturer's development center. A commercial development/demonstration unit is one on which preliminary testing or research is being carried out. Some of the gasifiers in this category are commercial prototypes for which a buyer is being sought, while others still require major development.

Pilot-scale gasifiers are those units that fall below a development-scale unit, both in size and, more importantly, in degree of commercial readiness. Pilot-scale units are developed primarily to test different design parameters before a full-scale unit is built.

Experimental or bench-scale gasifiers are those that are in the initial stages of development. These basic data collection units are used to test the viability of a particular gasification concept or feedstock. The time needed to convert a bench-scale unit to a commercial-scale unit will vary greatly with the manufacturer, since some companies have commercial experience in gasification of other fuels, and may only be modifying their original system for a new feedstock.

But the classification of processes is not absolute. Instead, it serves only to compare history and system successes of different manufacturers. Many developmental and pilot-scale units will achieve commercial status before 1984 if the market continues to develop as rapidly as most experts expect. Because field research is intensive and rapidly expanding, some firms would probably be classified differently if this review were done at some future date. By 1984, a doubling in the number of commercially available gasifiers is foreseeable, based upon extrapolation of recent trends. Table 1* summarizes the development status of commercial biomass conversion systems.

* All table and figure numbers refer to Appendix B.

Table 1

Expected Date of Commercial Availability

Gasification

System/Manufacturer	1979	1980	1982	1984	Not Considering Commercial Development
Alberta Industrial Dev.	X				
American Fyr. Feeder	X				
Andco, Inc.	X				
Applied Engineering Co., Inc.		X			
Biomass Corp.	X				
Bio-Solar		X			
Combustion Power			X		
Davy Powergas	X				
Dekalb Agresearch, Inc.					X
Duvant Moteurs	X				
Eco-Research	X				
Energy Products of Idaho			X		
Forest Fuels	X				
Foster Wheeler		X			
Halcyon	X				
Jamex		X			
Lamb-Cargate (Up-Draft)	X				
Lamb-Cargate (Fluid bed)		X			
Nichols Engineering & Research Corp.	X				
Vermont Wood Energy		X			
Westwood Polygas			X		
Wheelabrator Frye			X		
Wilputte Corp.					X
Wright-Malta		X			
Pyrolysis					
Alternative Energy Co.		X			
Energy Resources Co.	X				
Energy Recovery Research Group		X			
Environmental Energy Engineering		X			
Kelley Co.	X				
Tech Consultants				X	
Union Carbide				X	

Figure 1 shows the basic reactor designs of a wood gasifier. Each manufacturer will modify the basic design to meet the particular requirements of the user. Figure 2 presents a typical process flow diagram for a wood gasification system. Specific equipment will vary with the manufacturer.

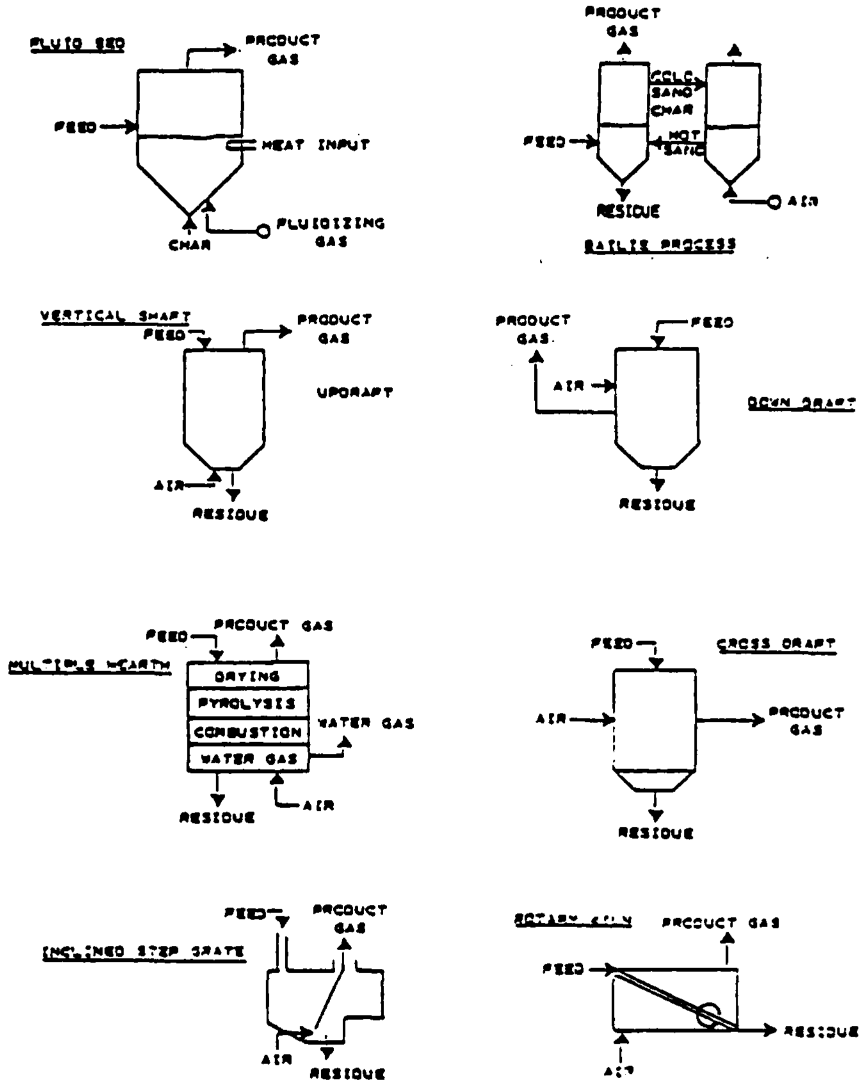

Figure 1. Basic configurations of available biomass gasification reactors.

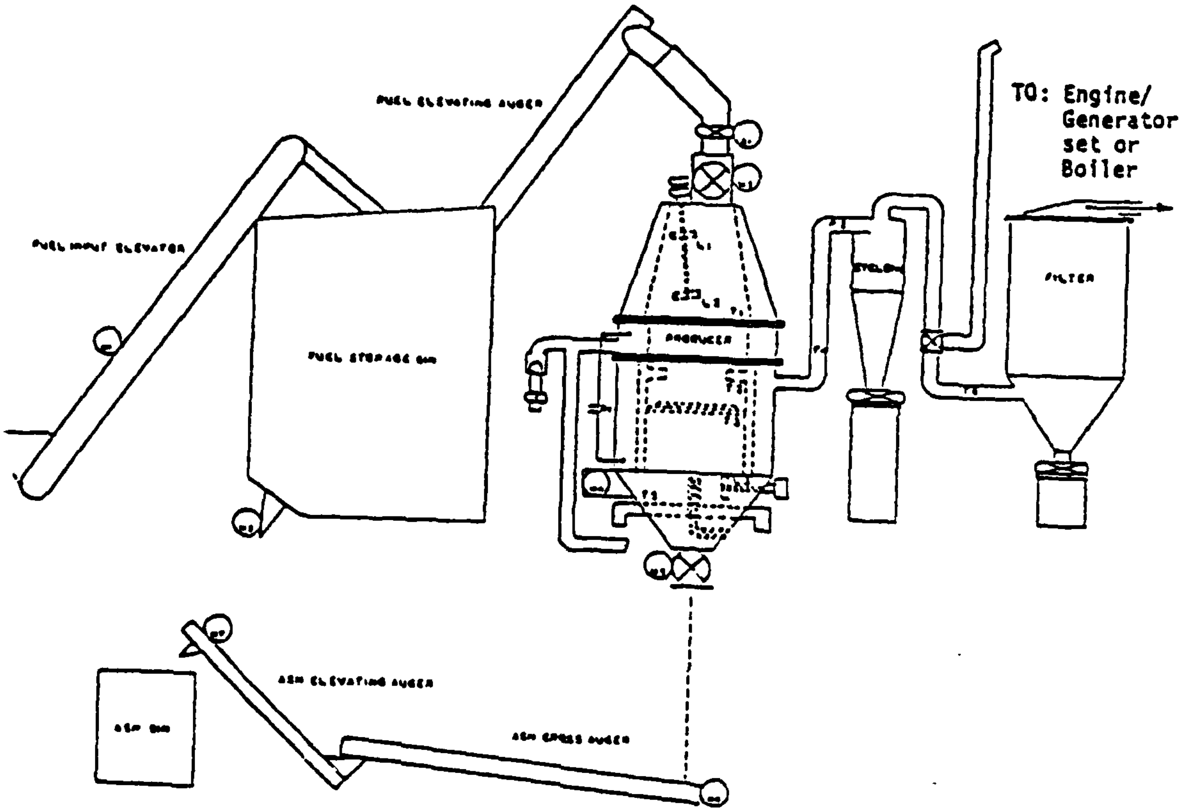

Figure 2. Example process flow for biomass gasification system. (From R.C. Lang, *Feasibility Study: Commercial Biomass Gasifier at State Central Heating and Cooling Plant* [California State Energy Commission, April 1978]).

4 STATUS OF COMMERCIAL BIOMASS GASIFICATION SYSTEMS

A list of 55 biomass gasification system manufacturers and research organizations was obtained from the literature and through private correspondence. The list was subsequently reviewed, and those researchers known not to be interested in commercial development were eliminated from further consideration (see Annex C). The three basic criteria for eliminating manufacturers from consideration were as follows:

- o Foreign technologies with no U.S. agents.
- o Lack of interest in commercial development.
- o Outdated information on company solvency or interest in the field.

The remaining firms were interviewed concerning process characteristics, history, and output data.

Tables 2 and 3 summarize the system characteristics for each of 30 manufacturers of biomass gasification and pyrolysis systems, respectively. Systems are categorized in the tables by primary reactor type (i.e., partial combustion [gasification] and oxygen-free combustion [pyrolysis]); and manufacturers are listed alphabetically by company name. These groupings are continued into the summary section and throughout the report.

Information contained in Tables 2 and 3 includes the stage of commercialization (proven, demonstration/developmental, pilot or experimental), reactor type utilized, feed fuels tested, energy content of products, design capacity, feed preparation, auxiliary power which supersedes the electrical or mechanical power requirement of the combustion air blowers and feed equipment, and whether the system is automated. Blank entries in the preparation requirements, auxiliary power requirement, and automation columns indicate that the information could not be obtained.

Alberta Industrial Developments, Ltd.

The AID system employs a fluidized-bed gasifier capable of producing either gas or char, depending upon user needs. The system was originated in 1972, when AID contracted with British Columbia Research to commercially develop the gasification unit. Past work includes an 18-in. (457.2-mm) bench-scale unit, and an 8-ft. (243.8-cm) diameter unit which was capable of handling 6,000 lb/hr (2,721.6 kg/hr) of feed. Present activities revolve around the commercialization of the gasifier.

Table 2

Overview of Commercial Biomass Gasification Systems

Manufacturer	Stage of Commercialization: Proven	Demon.	Pilot	Exper.	Reactor Type	Feed Fuel: Wood	MSW	Corn Cobs	Coal	Tires	Densified Wood Fuel	Products: LBG	MBG	Char	Oil	System Output Capacity (MBtuh)	Feed Preparation Required: Sizing (inches)	Moisture Content (%)	Auxiliary Power Required	Automated Operation	Comments
Alberta Industrial Dev.	X				FB	X						X				50			X		Two Units Each @ 25 MBtuh
American Fyr. Feeder	X				IS	X		X				X				0.25-60				X	Produce Retrofit Burner
Andco, Inc.	X				VS		X					X				24	<39				
Applied Engineering			X		UP	X		X			X	X				8		50			
Biomass Corp.		X			DD	X						X				20	.5-3			X	
Bio-Solar				X	UP						X	X					Pelletizing				
Combustion Power				X		X						X									Paper Study of Various Designs
Davy Powergas	X				5 Types	X			X			X									
DeKalb Agresearch	X				UP			X				X				10		10			For In-House Seed Drying
Duvant Moteurs	X				DD	X						X				1-6.4	<12	10-20		X	Have I.C. Engine for Elec. Gen.
Eco-Research			X		FB	X	X					X				16		35-55	X	X	
Energy Products of Idaho				X	FB	X						X							X		
Forest Fuels		X			UP	X						X				1-30	<1.5	15-20		X	
Foster Wheeler				X	UP	X						X				20-120					Pressurized
Halcyon		X			UP	X						X				0.25		65			
Jamex		X			Cross	X		X				X				0.5-1.5		7-45		X	
Lamb-Cargate	X				UP	X						X				25					
Lamb-Cargate		X			FB	X						X				4	<2		X		
Nichols	X				MH	X						X		X		80-90				X	Char Energy Content=12,000 Btu/l
Vermont Wood Energy			X		UP	X						X				.05-0.1		20			Home Size Units
Westwood Polygas		X			UP	X						X				20		35-50		X	
Wilputte Corp.	X				Rot-VS				X			X				50	<4		X		
Wright-Malta			X		Rot-Kiln	X							X			3			X		Steam Gasification @ 300 psi

Table 3

Overview of Commercial Biomass Pyrolysis Systems

	Stage of Commercialization				Reactor Type	Feed Fuel					Products				Design Capacity Input (ton/day)	Feed Preparation Required		Auxiliary Power Required	Automated Operation	Comments
	Proven	Demon.	Pilot	Exper.		Wood	MSW	Tires	Manure	Sludge	LBG	MBG	Char	Oil		Sizing (inches)	Moisture Content (%)			
Alternative Energy Co.			X		DD	X		X			X				25			X		Pressurized, steam injection
Energy Resources Co., Inc.		X			FB	X			X		X		X	X	20-150			X		
Energy Recovery Research Group			X		VS			X							20					
Environmental Energy Engineering, Inc.		X			FB	X	X					X			50	1.25	20	X		Bailie Process*
Kelley Co.	X				UP	X					X				28		10			
Tech Consultants		X			UP	X	X			X	X		X	X	50		7			Product percentages adjustable
Union Carbide		X			VS	X	X					X			200	Compaction				Pure O_2
Wheelabrator Frye		X			FB	X	X					X			50	1.25	20	X		Bailie Process*

*Both companies indicated possession of technology; questions exist as to marketing control.

KEY:

<u>Energy Content of Products</u>

LBG = <250 Btu/scf
MBG = 250-500 Btu/scf
Char = ∿12,000 Btu/lb
Oil = ∿100,000 Btu/gal

<u>Reactor Type</u>

FB = Fluid bed
UP = Up-draft
DD = Down-draft
VS = Vertical shaft (will be either up-draft or down-draft)
MH = Multiple hearth
IS = Inclined step grate
Cross = Cross draft
ROT = Rotary

<u>Auxiliary Power Requirements</u>

Mechanical or electrical use above combustion air (or feed movement) needs.

Many types of fuels have been tested, including sawdust. The size range of available units is ~20-60 MBtuh, though multiple units can be arranged. AID does not have a proven commercial unit on line, though their prototype reactor has 6,000 hours of operating time. An 86 percent thermal efficiency is claimed up through gas production, including the sensible heat of the gas.

American Fyr-Feeder

Fyr-Feeder has an inclined step-grate gasifier that is close-coupled to a conifer burner which is also produced by Fyr-Feeder. The gasifier is in commercial production, and 20 units have been installed since 1977. Available gasifier capacities range from 250-KBtuh to 60-MBtuh unit. A wide variety of feed fuels can be used, including green woodchips, sawdust, hogged fuel, wood pellets, corncobs, and nut shells. The system controls can be automated, although manual ash removal is required once per day during normal operation.

ANDCO, Inc.

ANDCO, Inc., produces a vertical shaft gasifier of a design similar to slagging coal gasifiers. Most work has been done using municipal solid waste as a feedstock. At least three such units are operating in Europe. ANDCO is interested only in selling the gasifier, and does not wish to become involved in total system design or supply. Developmental work has been underway since 1970, when the first demonstration unit was built.

Applied Engineering Company

Applied Engineering Company, along with Georgia Forestry and Weyerhaeuser, built and tested an updraft biomass gasifier in 1977. The unit was operated on corn crops, wood chips, and wood pellets, and produced 8 MBtuh of fuel gas. This particular gasifier is no longer in use. A commercial demonstration unit of similar design will be installed by early 1980.

Biomass Corporation

Biomass Corporation has a downdraft gasifier design ready for commercial application, and a hot raw gas system whose efficiency is greater than 85 percent. The firm is capable of total system design. A 0.75-MBtuh unit was delivered to a Canadian research foundation (Forintek) for use as a demonstration and testing facility. The State of Minnesota is going to use a Biomass Corporation gasifier fueled with peat for the production of 150 kW of electricity. The State of Alaska will use a similar unit fueled with coal and/or biomass. The Biomass Corporation gasifier has fully automated fuel feed and ash removal systems. Multiple units can be linked together to produce larger quantities of gas. Future plans call for an investigation of medium- or high-Btu gas production using pure oxygen in place of air.

Bio-Solar Research and Development Corporation

Bio-Solar is developing a gasifier to utilize its densified wood fuel, Woodex®. The gasifier is in experimental stages of development. One year is anticipated before a commercial level is achieved.

Combustion Power Company, Inc.

CPC has been investigating gasification for 1-1/2 years, but no developmental work has been completed at present. The company anticipates a pilot-scale reactor within one year. At least two years of work are expected before any commercial systems become available.

Davy Powergas, Inc.

Davy Powergas is a commercial supplier of gasification equipment. The company offers five types of gasifiers: a fixed-bed design with over 1,000 operating units, 40 of which are wood-fueled; a two-stage gasifier; a Winkler gasifier; a Texaco-design gasifier; and a CO_2 acceptor system. Developmental work has been performed primarily with coal, though wood has also been utilized. No additional data was available.

DeKalb AgResearch

DeKalb is a corn seed supplier that uses waste cobs to fuel an in-house-developed gasifier. The unit is rated at 1.6 MBtuh, and has over 1,000 hours of operating experience. The unit has an operating range of between 0.2 and 3 MBtuh. The company believes that it can use one hundred 10-MBtuh gasifiers, and has set 1980 as its target date for production of these systems. No commercial marketing activities are anticipated in the near future.

DuVant Moteurs

DuVant originally developed downdraft wood gasifiers in the 1920's. The present system utilizes the product LBG to power a DuVant dual-fueled internal combustion engine for electric power generation. The gas is mixed with diesel oil in output-controlled ratios. Under normal operating conditions with dried wood feed, the diesel/gas ratio is 1:9. Engines up to 1,100 hp can be purchased. DuVant has sold 10 complete units since 1974.

Eco-Research, Ltd.

Development and testing of a fluidized-bed gasifier has been underway since 1976. Eco-Research is presently testing a 25-ton/day pilot plant and expects to be ready for commercial production by October 1979. The pilot unit has been operated continuously and is automated. There are future plans for an investigation of oxygen gasification to increase the energy content of the gas, and for commercialization of the fluidized-bed system.

Energy Products of Idaho

Energy Products of Idaho manufactures and constructs wood energy systems based on a fluid-bed combustor. Work in gasification is in the experimental stages. The firm expects to have a commercial gasifier on the market within five years.

Forest Fuels Manufacturing

Forest Fuels is presently marketing an updraft, traveling grate gasifier for close-coupled boiler operation. Developmental work has been underway for approximately five years. A fixed-grate, demonstration-scale gasifier of similar design has been in operation for over three years. The firm offers gasifiers ranging in capacity from 1 MBtuh to 30 MBtuh output. A Forest Fuels gasifier was installed at a hardwood kiln in Georgia in 1976. The unit produces 12-13 MBtuh and powers a 200-hp boiler. The experience gained at the Georgia plant has been used to improve the product, automate the controls, and overcome problems in the design. The gasifier appears to be ready for marketing, though development is still underway.

Kearsarge Reel Company, Warner, New Hampshire, is using a Forest Fuels gasifier to produce heat during winter months. All fuel is produced by in-house processes, and a 50 percent cost saving is realized over heating oil. Kearsarge Reel has been a test facility for Forest Fuels since 1975, when the first gasifier was constructed.

Foster Wheeler Energy Corporation

Foster Wheeler is experimenting with a proprietary wood gasifier design. The reactor is updraft, pressurized to 30 in. H_2O, and designed to operate in a range between 20 to 120 MBtuh. Foster Wheeler has been manufacturing coal gasification equipment for 25 years, and is applying this experience to wood. One year of additional research is required before commercialization is considered.

Halcyon, Inc.

Halcyon builds updraft gasifiers for direct gas use in modified diesel engines. The gas is cleaned of water vapor before being injected into the engine. The company is currently constructing three 25-MBtuh plants, which are expected to be on line in 3 to 4 months. Future plans are for the development of worldwide markets for the existing gasifier and additional research on an MBG plant.

Jamex, Inc.

Jamex is currently manufacturing a 5-MBtuh cross-draft gasifier for use by Litton Industries, Sioux Falls, South Dakota. The gasifier is the fourth model in the development process. The unit is semimobile and can handle a variety of feedstocks and moisture contents. Jamex is primarily a supplier of grain-handling equipment, and has used this experience to simplify the feed mechanisms involved in its gasification system.

Lamb-Cargate Industries, Ltd.

Lamb-Cargate has two types of gasifiers in commercial production. A fluidized-bed (British Columbia Research) gasifier is in the demonstration stage, operating in Hudson Bay, Saskatchewan, on green hog wood to produce electricity for Saskatchewan Power Company. The firm also has updraft, dual-chamber gasifiers operating in Canada and New Zealand. Output of these gasifiers is rated at 25 MBtuh. The units are being used in kiln and pulp dryer applications. The company has plans to scale up the gasifiers into the 150 MBtuh range for boiler, kiln, and dryer applications.

Nichols Engineering

Nichols has been supplying commercial gasifiers since the 1930's. The firm has installed a total of 35 units, with six automated units having been constructed in the past six years. The process employs a multiple-hearth reactor, 22 ft. (6.71 m) in diameter and 60 ft. (18.29 m) high, which is rated at 80 to 90 MBtuh output. The products are a LBG and a char. The energy content of the gas is 100 to 450 Btu/scf, while the char has an energy content of 12,000 Btu/lb. The process produces no oils. Nichols gasifiers are in operation in the south and southeast United States, and use wood and wood wastes as feed.

Vermont Wood Energy Corporation

The Vermont Wood Energy Corporation is in the pilot stages of developmental work on small-scale gasifiers for home heating applications. The system is designed as an updraft, close-coupled gasifier to operate on wood and wood wastes. Current activities include automation of the feed mechanisms. The firm expects to be in limited production by early 1980, if results warrant continued development. Size range of these gasifiers is expected to be between 50 and 100 KBtuh.

Westwood Polygas

Westwood is developing an updraft, 20-MBtuh gasifier to operate on hog fuel. The gasifier was first developed by Moore Canada, from which Westwood took over the process rights in 1976. Current activities include utilizing a commercial-size reactor (9-ft. [2.74-m] diameter) for developmental research and testing.

Wilputte Corporation

Wilputte has been involved in gasification since early in this century. Developmental work started on coal, switched to wood, then to oil, and is now back to coal. The company uses a rotating-grate, vertical-shaft reactor capable of producing 50 MBtuh when fueled with coal. The gas has a low energy content, varying slightly with the type of coal used. The firm believes that its process can be adapted to wood, but is not investigating this area.

Wright-Malta

Wright-Malta is presently in the product development stage of its gasification research. Investigation of steam gasification, using a pressurized rotating-kiln reactor, is presently underway. Pressures up to 300 psi are generated in the gasifier, which has been fueled by wood chips and other forms of biomass. The product is a medium-energy gas of approximately 500 Btu/scf. Work is being done for the Department of Energy as part of DOE's biomass-to-energy program. Commercial applications of this technology are not expected before late 1980.

Alternative Energy Company

AEC has a steam-injected blue water gas generator (280 Btu/scf) designed to utilize tires, wood wastes, or any carbonaceous material. The system is in the commercial development/demonstration stage. Heat for the pyrolysis reaction will be generated electrically, using a freon engine to produce the electricity. Tests have been conducted on a pilot-scale reactor, and on a test unit of 20-ton/day capacity. A 25-ton/day prototype is scheduled to begin operation mid-August, 1979. The total system has not been demonstrated as a unit.

Energy Resources Company, Inc.

ERCO has been involved in gasification since 1975. Current gasifier work centers around the commercial development and marketing of a fluidized-bed unit. A demonstration-scale gasifier has been run for approximately 900 hours. ERCO indicates that the system is ready for commercial-scale operation, and will guarantee output performance. ERCO is currently developing a mobile biomass pyrolysis unit for the State of California.

Energy Recovery Research Group

ERRG is commercializing a pyrolysis system to convert old tires to a fuel gas. Some work has been done with wood. The downdraft reactor can handle 20 tons/day. Developmental work has been underway for 1-1/2 years.

Environmental Energy Engineering, Inc.

EEEI is investigating a number of different conversion systems. Two are fluidized-bed designs, one is a downdraft design. One of the fluidized-bed designs has been commercialized in Japan. (It is a dual fluidized-bed reactor where char from the pyrolysis reactor is combusted in the second reactor vessel to produce the heat needed for pyrolysis.) The Japanese unit can handle 200 tons/day of municipal solid waste, and has been operating for approximately one year. Two similar units are presently under construction. The product is an MBG (320 to 400 Btu/scf). Discussion with the Japanese company has been initiated to determine the feasibility of commercialization in the United States.

Kelley Company, Inc.

The Kelley pyrolytic incinerator has had commercial applications for many years. A total of 550 have been sold. The system employs a two-stage, updraft pyrolysis reactor that operates on 1/3 stoichiometric air requirements. The reactors are close-coupled to boilers, and are capable of producing 18 MBtuh. Developmental work has eliminated exhaust stream dampers, and allows full modulation of output. A low-moisture content fuel is required (<10% H_2O) with a rated efficiency of 65 percent.

Rockwell International's heavy equipment plant in Marysville, Ohio, is using a Kelley Pyrolytic incinerator to produce steam and hot water for its many processes. The unit uses 1,200 lb/hr of boxes, shipping crates, and computer paper as fuel. The plant is experiencing a $100,000/yr savings on fuel and trash removal cost. The payback period is expected to be 3-1/2 to 4 years.

Tech Consultants

Tech Consultants, formerly Tech Air, has developed a vertical-shaft, starved-air pyrolysis reactor. A demonstration unit of 50 dry tons/day was operational for 18 months. The pyrolysis system can be adjusted for different output percentages of gas, oil, and char. The gas has an energy content of 200 Btu/scf, the oil approximately 100,000 Btu/gal, and the char from 10,000 to 11,000 Btu/lb. The firm has used the pyrolytic oils to clean the gas stream with excellent results. The parent company, American Can Company, has responsibility for any commercialization of the system, and does not expect any major activities on wood systems in the near future.

Union Carbide

Union Carbide is doing extensive work in municipal solid waste conversion. A 200-ton/day demonstration plant is operating in South Charleston, West Virginia. The system uses pure oxygen to produce an MBG (400 Btu/scf) by pyrolysis. The company believes that wood could be utilized, but is not actively pursuing this as an area of primary development.

Wheelabrator-Frye

Wheelabrator-Frye has a dual fluidized-bed reactor design (Bailie Process) ready for commercial demonstration, but is waiting either for a market to develop or a government demonstration grant before proceeding with commercialization. The system produces a gas containing 400 to 500 Btu/scf, and has been tested and operated in Japan. The process is designed to utilize any type of solid waste, including biomass. The units in Japan each process up to 50 tons/day of municipal solid waste, with wood comprising a portion of that tonnage.

5 THE COST OF BIOMASS GASIFICATION SYSTEMS

The capital cost of a typical biomass gasification system is distributed as shown in Figure 3. The reactor normally comprises only 20 percent of the capital cost. The remaining 80 percent is expended on feed equipment, engineering, and instrumentation. These estimates do not include the cost of equipment needed to transport the raw fuel to the gasifier site.

Capital costs vary significantly with the fuel feed characteristics and other site-specific factors. The following list presents the range of capital cost expected for a corresponding gasification capacity:

Capacity (MBtuh)	Capital Cost ($)
10-20	200,000 - 400,000
20-30	250,000 - 600,000
30-50	500,000 - 1,000,000
>50	1,000,000

Detailed capital cost estimates for commercial gasification systems could not be obtained from any manufacturers because (1) system designs are very site-specific; (2) materials handling equipment, the largest portion of system cost, is specific to feed fuel; and (3) the level of automatic control and instrumentation required will vary with the client specifications.

Operating and maintenance costs can be estimated with more certainty. The normal wood gasifier conversion process is nearly 100 percent self-sustaining. The only auxiliary fuel required is for start-up. Minimal electrical power is needed to operate blowers, controls, and feed mechanisms. A lumber kiln in Georgia, for example, is operating a 12-MBtuh gasifier, and spends only $200 per month for electric power to operate the system. Fluidized-bed reactors will consume greater quantities of electricity for bed fluidization.

The labor required for gasifier operation is low. No more than one trained worker is required to operate an automated gasifier system, while personnel requirements for boiler and fuel-handling activities are similar to those at a coal-fired steam plant. In most cases, the gasifier systems are automated (self-regulating) and alarmed.

Maintenance requirements are low, and the repair history of most operating gasifiers is very good. Maintenance costs should continue to diminish as the technology advances.

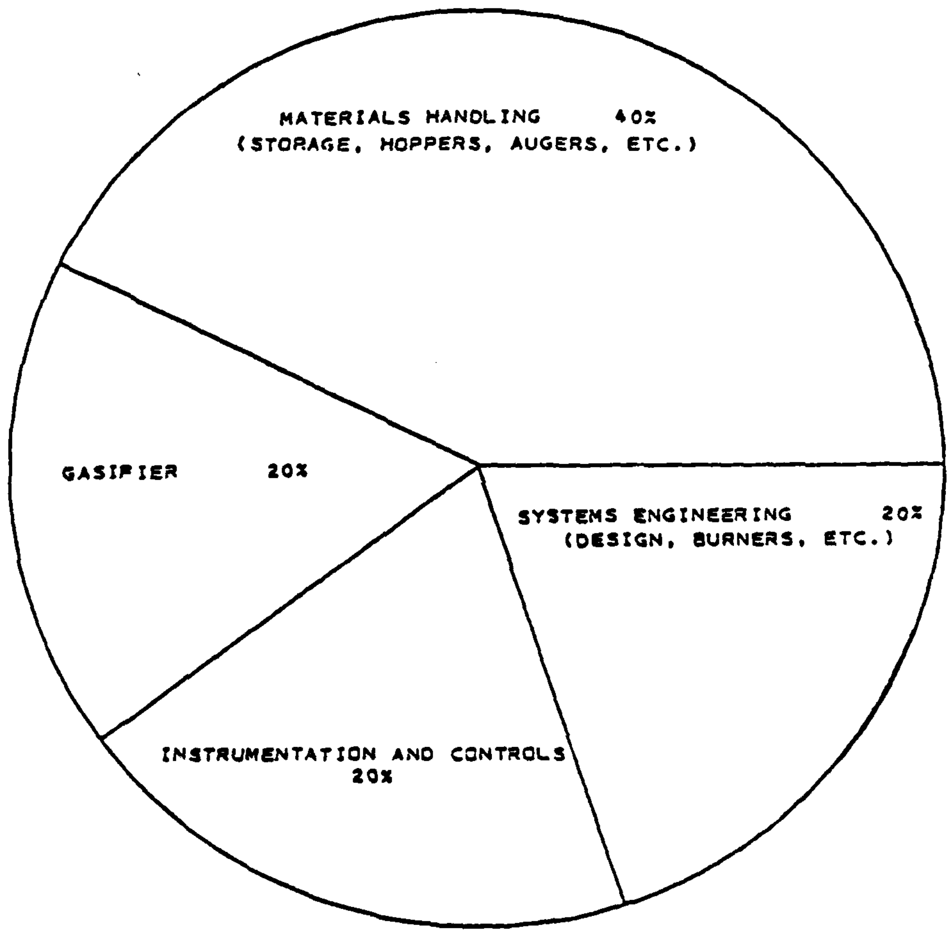

Figure 3. Distribution of capital costs for biomass gasification systems. (From R.O. Williams, private communication.)

Some gasifier reactors require water injection, but most systems need no additional water or chemical beyond that required for boiler operation. Feed cost and availability determine the economic viability of gasification in a particular geographic area. A delivered price of $20 or $30/ton of feed material is considered to be the present upper limit to cost-effective operation. The exact limit will vary from area to area, and can be expected to increase as the price of competing fuels increases. In locations where the availability of fossil fuels is uncertain, the feasibility of gasification appears to be even more favorable.

An overall technical and economic ranking of the different systems would be premature at this time. As shown earlier, there are 13 manufacturers actively marketing commercial installation-scale gasifiers in 1979. By 1980, this number will increase to at least 20. Most of these firms are willing to guarantee the performance of their equipment. Therefore, selection of a gasification system for a particular application should not be limited to those systems in commercial operation. A comparative cost analysis should be based on the specific application, as the basic capital cost for most systems is similar.

6 CONCLUSIONS AND RECOMMENDATIONS

Conclusions

The range of system capacities of interest to the Army is 2.0 to 250 MBtuh. From this investigation, it is clear that the capacity requirement can be met using commercial biomass gasification systems. No single unit is able to produce 250 MBtuh, but multiple smaller reactors (up to 150 MBtuh) can be combined to meet a higher capacity specification.

Biomass conversion systems can have a large and an immediate impact as a source of alternate or supplemental fuel for existing boilers now using oil or natural gas. The conversion process is neither difficult or prohibitively expensive. The retrofitting process will include the replacement of burners, expansion of duct work, and enlarging the draft fan capacity. A number of manufacturers produce special burners for retrofitting boilers. Derating of the boiler is minimal in most cases.

The near-term potential for wood gasification/pyrolysis conversion systems to provide an alternative fuel supply at Army installations is good.

Recommendations

The Army should pursue gasification of biomass as an alternate energy source. To facilitate this transition, the following activities should be undertaken:

- A site should be selected for a demonstration facility. This facility will assist the Army in further evaluating biomass gasification on the installation scale, as well as the compatibility of Army boilers with biomass-derived fuel. The demonstration will also enable the Army to develop a detailed system maintenance and cost history, which will become important if gasifier use is promoted within the Army.

- A feasibility study should be undertaken to (1) develop a better estimate of capital and operating costs of a gasifier system at the selected installations; (2) determine the availability of feed fuel at that location; (3) estimate the transportation requirements for the fuel; (4) identify manufacturers who can supply the necessary equipment; and (5) define the manpower requirements to operate the unit.

- A survey of all Army facilities should be performed to identify those installations where gasification technology can best be implemented. The survey should also determine long-term fuel availability at those facilities.

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ANNEX A:

SUMMARY OF ENVIRONMENTAL EFFECTS
OF BIOMASS GASIFICATION

The two principal environmental impacts of concern during biomass gasification are: (1) air emissions from the gasification reactor and subsequent conversion operations, and (2) the disposal of solid process residues. A preliminary secondary concern is the effect of biomass harvesting on the local environment, including the effects of transportation and storage requirements

The principal constituent of gasification emissions is particulate matter, resulting from both fuel processing and the gasification/combustion process. Fugitive emissions occur during the loading and unloading of fuel, storage and handling operations, and fuel size reduction (if any). The particulate emissions resulting from gasification/combustion can be controlled using conventional technology, such as baghouses[18]. Gaseous emissions (NO_x, CO, HC, and SO_x) do occur, but the emission factors are much lower than for fossil fuel-fired boilers[19]. This reduction in emissions resulting from a switch to biomass gasification should offset the increase in CO and HC emissions from transport trucks; movement of the biomass feed from the source to the plant will probably be served by trucks rather than trains. Tests conducted by the California Air Resources Board[20] at the State Printing Office gasification plant (1978) showed that SO_2 emissions were near the detection limit, and that NO_x emissions were measured at 0.703 lb/hr averages compared to the Sacramento area limit of 4.09 lb/hr.

The disposal of solid residue from gasification is not considered a problem. An estimated 2 to 3 percent by weight of the incoming feed remains as ash[21]. The disposal of this ash can be safely accomplished in a sanitary landfill[22], although no information on specific residue characteristics could be found in the literature.

18 Environmental Science Associates, Inc., *Environmental Impact Report: Alternative Fuel System - Organic Waste to Energy Facility, Capitol Area Central Heating and Cooling Plant* (Environmental Science Associates, Inc., June 1979), p 39.

19 Environmental Science Associates, Inc., p 38.

20 R.C. Lang, *Feasibility Study: Commercial Biomass Gasifier at State Central Heating and Cooling Plant* (California State Energy Commission, April 1978).

21 R.C. Lang, p 16.

22 R.C. Lang, p 38.

The secondary effects of biomass harvesting should be of concern to the Army, particularly if the source of the biomass feed is within the confines of the installation. Secondary effects include the impact of biomass harvesting on water quality, land use, soil erosion patterns, soil nutrient balance, health and safety of employees, and aesthetics. With proper harvesting and planting techniques, the forest productivity can actually be increased. Forestry experts should be consulted when potential sources of biomass are being investigated.

ANNEX B:

BIOMASS GASIFICATION/PYROLYSIS MANUFACTURERS

Eastern Zone

ANDCO, INC.
25 Anderson Road
Checktowaga, NY
(716) 896-8181
Mr. Stan Mark

APPLIED ENGINEERING CO.
Box 1337
Orangeburg, SC 29115
(803) 534-2424
Mr. Dean Harris

DUVANT MOTEURS
B.P.Z. 36
Valenciennes, France 59308
Represented by:
INDUSTRIAL DEVELOPMENT AND
PROCUREMENT
Old Country Road
Carle Place, NY 11514
(516) 248-0880
Mr. George Bonnici

ECO-RESEARCH LIMITED
P.O. Box 200, Station A
Willowdale, Ontario MZN 558
(416) 226-7351
(613) 544-7196
Mr. John Black

ENERGY RESOURCES CO., INC.
185 Alewife Brk. Parkway
Cambridge, MA
(617) 661-3111
Mr. Dan Traxler

FOREST FUELS, INC.
7 Main Street
Keene, NH 03431
(603) 357-3311
Mr. Tevis Morrow

FOSTER WHEELER ENERGY CORP.
110 South Orange Avenue
Livingston, NJ 07039
(201) 533-2667
Mr. R.J. Broeker

HALCYON, INC.
Maple Street
East Andover, NH 03231
(603) 735-5356
Mr. Bill Finnie

NICHOLS ENGINEERING AND RESEARCH
CORP.
Homestead and Willow Road
Belle Mead, NJ 08502
(201) 359-8200
Mr. William Trethaway

TECH CONSULTANTS
P.O. Box 910
Smyrna, GA 30081
(404) 435-2005
Dr. Max Bowen

UNION CARBIDE CORP.
270 Park Avenue
New York, NY 10017
(212) 551-2345
Mr. David Valley (714) 291-9691

THE VERMONT WOOD ENERGY CORP.
P.O. Box 280
Stowe, VT 05672
(802) 253-7220
Mr. Phil Rich

Eastern Zone (continued)

ENVIRONMENTAL ENERGY ENGINEERING, INC.
P.O. Box 4214
Morgantown, WV 26505
(304) 328-5116
Dr. Richard Bailie

WHEELABRATOR-FRYE INCINERATION, INC.
600 Grant Street
Pittsburgh, PA 15219
(412) 288-7461
(603) 926-5911 - Energy Sys. Div.
Mr. John Rohrer

WILPUTTE CORP.
152 Floral Avenue
Murry Hill, NJ 07874
(201) 464-5900
Mr. J.C. Eck

WRIGHT-MALTA CORP.
Plains Road
Battston Spa, NJ 12020
(518) 899-2227/2350
Mr. John Coffman

Central Zone

DAVY POWERGAS, INC.
6161 Savoy
Houston, TX
(713) 782-3440
Mr. Stewart Brown

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411 South Sixth
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(815) 758-3461
Mr. Stan Bozdech

JAMEX, INC.
St. Peter, MN
(507) 931-6750
Mr. Emerson Wells

KELLY CO., INC.
6720 North Teutonia
Milwaukee, WI
(414) 352-1000
Mr. Ksel Erlandsen

AMERICAN FYR-FEEDER
1265 Rand Road
Des Plains, IL 60615
(312) 298-0044
Mr. Gauger

Mountain Zone

ALBERTA INDUSTRIAL DEVELOPMENT LTD.
1704 Cambridge Building
Edmonton, Alberta, Canada T5J
(403) 429-4094
Mr. Richard Assaly

Pacific Zone

ALTERNATIVE ENERGY COMPANY
4800 Manzanita Avenue, Suite 13
Carmichael, CA 95608
(916) 483-2761
Mr. Jack Cunningham IV

BIOMASS CORP.
951 Live Oak Boulevard
Yuba City, CA
(916) 674-7230
Mr. Ted Crane - Dr. Robert Williams

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P.O. Box 762
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(503) 686-0765
Mr. Mo Ottomeier

COMBUSTION POWER CO., INC.
1346 Willow Road
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(415) 324-4744
Dr. Ming Lu

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Mr. William McCarty

ENERGY RECOVERY RESEARCH GROUP, INC.
3420 Ocean Park Boulevard
Suite 1030
Santa Monica, CA 90405
(213) 450-5679
Mr. Philip Junkins

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1135 Queens Avenue
New Westminster, British Columbia
(604) 521-8821
Mr. Peter Rada

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1444 Alberni Street
Vancouver, British Columbia, Canada
V6G 2Z4
(604) 684-9371
Mr. Richard Kania
(604) 682-7841 - INTEG
1155 West Pender
Vancouver, B.C.
V6E 2P4

ANNEX C:

BIOMASS GASIFICATION/PYROLYSIS MANUFACTURERS AND USERS ELIMINATED FROM CONSIDERATION*

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CAN-AM SALES CORP. [2]
P.O. Box 158
Skaneateles, NY 13152
(315) 685-5611

INTERPINE LUMBER CO. [4]
Picayume, NH 03278
(603) 798-5912

KEARSARGE REEL CO. [4]
Warner, NH 03278
(603) 938-2266

QUEBEC ELECTRO MARINE DIESEL, INC. [3]
Beaconsfield, Quebec, Canada

ROCKWELL INTERNATIONAL [4]
Marysville, OH 43040
(513) 644-3015
Mr. Bill Smith

WESTERN VIRGINIA UNIVERSITY [4]
Morgantown, WV 26505
(304) 293-3280

WOODALL-DUCKHAM, LTD. [2]
921 Penn Road
Pittsburgh, PA 15220
(412) 471-5350

YORK-SHIPLEY, INC. [2]
P.O. Box 349
York, PA 17405
(717) 843-8831

Central Zone

BASIC ENVIRONMENTAL ENGINEERING, INC. [2]
21 West 161 Hill Street
Glen Elly, IL 60137
(312) 469-5340

COPELAND SYSTEMS, INC. [2]
200 Spring Road, Suite 300
Oak Brook, IL 60521
(312) 986-8564

DEERE AND CO. [2]
Technical Center
3300 River Drive
Moline, IL 61265
(309) 757-5275

PIONEER HI-BRED INTERNATIONAL [2]
100 West Jefferson Street
Tipton, IN 46072
(317) 675-2101

TEXAS TECH UNIVERSITY [4]
Department of Chemical Engineering
Lubbock, TX 79409
(806) 742-3553

UNIVERSITY OF MISSOURI [4]
Rolla, MO 65401
(314) 341-4151

Pacific Zone

BATTELLE PACIFIC NORTHWEST LABORATORIES [4]
Battelle Boulevard
Richland, WA 91935
(509) 946-2432

BATTELLE COLUMBUS [4]
505 King Avenue
Columbus, OH 43201
(614) 424-6424

BRITISH COLUMBIA RESEARCH [4]
3650 Wesbrook Ma.
Vancouver, British Columbia V6S 2L2
(604) 224-4331

Pacific Zone (continued)

CENTURY RESEARCH [3]
1635 South Vermont
Gardena, CA
(213) 327-2405

EUGENE WATER AND ELECTRIC BOARD [2]
500 East 4th Street
Eugene, OR 97440
(503) 484-2411

GARRETT ENERGY RESEARCH AND ENGINEERING [4]
911 Bryant Place
Ojai, CA
(805) 646-0159

OCCIDENTAL RESEARCH CORP. [4]
2100 Southeast Main
Irvine, CA
(714) 957-7000

UNIVERSITY OF CALIFORNIA AT DAVIS [4]
Agricultural Engineering Department
Davis, CA 95616
(916) 752-1421

Foreign

DISTIBOIS [1]
RANS - 39700
Orchamps (Jura), France

IMBERT AIR GASIFIER [1]
Steinweg Nr. 11
5760 Arnsberg 2, Germany

STE ALSACIENNE DE CONSTRUCTIONS MECANIQUE [1]
Department Diesel
1 Ruc de la Fondirie
Mulhous Ht Rhin, France

WELLMAN INCANDESCENT, LTD. [1]
Cornwall Road, Smethwick
Warley, England
(021) 558-3151

*The four basic criteria for eliminating systems from consideration were as follows:

1. Foreign technologies with no U.S. agents.

2. Lack of interest in commercial development.

3. Outdated information on company solvency or interest in the field.

4. User or research organization.

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Collishaw, Anslie N.
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